CEPC and FCCee parameters from the viewpoint of the beam-beam and electron cloud effects

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CEPC Parameters

Y. Zhang, CEPC conference Nov. 2017, IHEP

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	30	30	2.9
Bending radius (km)	10.9		
Momentum compaction (10^{-5})	1.14		
β_{IP} x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
RF Phase (degree)	128	134.4	138.6
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)	650		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
F (hour glass)	0.93	0.96	0.986
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.0	4.1	1.0

FCCee parameters

D. Shatilov,
Aug-Oct 2017

parameter	Z	W	H (ZH)	ttbar	ttbar
beam energy [GeV]	45.6	80	120	175	182.5
arc cell optics	60/60	90/90	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7	2.9
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
length of interaction area [mm]	0.42	0.5	0.9	1.95	2.0
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)	(0.553, 0.59, 0.0349)
longitudinal damping time [ms]	414	77	23	7.5	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.10	0.44	2.0	9.5	10.9
RF acceptance [%]	1.9	1.9	2.3	5.0	4.7
energy acceptance [%]	1.3	1.3	1.5	2.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192	0.153 / 0.195
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33	1.0 / 1.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
number of bunches / beam	16640	2000	393	48	39
beam current [mA]	1390	147	29	6.4	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**7.8**	**1.8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157	0.090 / 0.148
luminosity lifetime [min]	70	50	42	39	39
time between injections [sec]	122	44	31	32	32
allowable asymmetry [%]	±5	±3	±3	±3	±3
required lifetime by BS [min]	29	16	11	12	12
actual lifetime (w) by BS [min]	> 200	20	20	24	25

Major difference between CEPC and FCCee

	CEPC-Z	FCCee-Z	CEPC-H	FCCee-H
ε_x(nm)/ ε_y (pm)	0.17/2.9	0.27/1.0	1.21/3.6	0.63/1.3
β_x/ β_y (mm)	360/2	150/0.8	360/2	300/1
σ_z(mm)/$\sigma_{z,BS}$(mm)	3.67/5.18	3.5/12.1	2.72/3.48	3.15/4.9
θ(mrad), θ_P	0.0165, 10.8	0.015, 28.5	0.0165,2.75	0.015, 5.3
N_e	1.6-4.8x10^{10}	17x10^{10}	12.9x10^{10}	15x10^{10}
N_{bunch}, t_{sp} (ns)	10900, 35	16640, 20	286	393
L_{tot} ($cm^{-2}s^{-1}$)	1-9	230	2.0	7.8
ξ_x/ ξ_y	0.005-0.015/ 0.0165-0.048	0.004/0.133	0.024/0.094	0.016/0.108

$$L = \frac{N\xi_y}{2r_e\beta_y^*}f$$

These are not latest parameters

H: Luminosity is 2x10^{34} and 8x10^{34} $cm^{-2}s^{-1}$ for CEPC-H and FCCee-H. The difference is due to beta (1:2) and beam current (1:2). Similar beam-beam tune shift ~0.1/IP.

Z: Lum for FCCee-Z is 230-30 times higher than CEPC-Z. Beam current of FCC is 10-3 times higher. Target beam-beam parameter of FCC is 8-3 times higher. β^*_y=2mm,0.8mm.

Issues related to beam-beam effects

- Beamstrahlung and beam life time mainly in Higgs factories.
- Beamstrahlung is also important in Z for bunch lengthening.

- Coherent beam-beam instability mainly in Z factories.

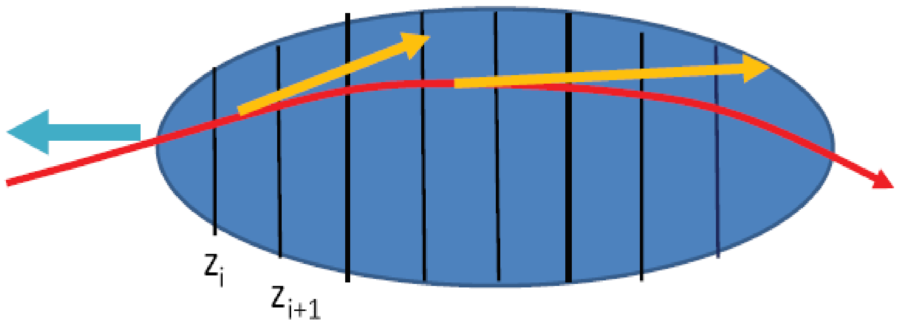
- Beam-beam simulations, especially strong-strong simulations, give answers feasibility of the future circular colliders, CEPC, FCCee…

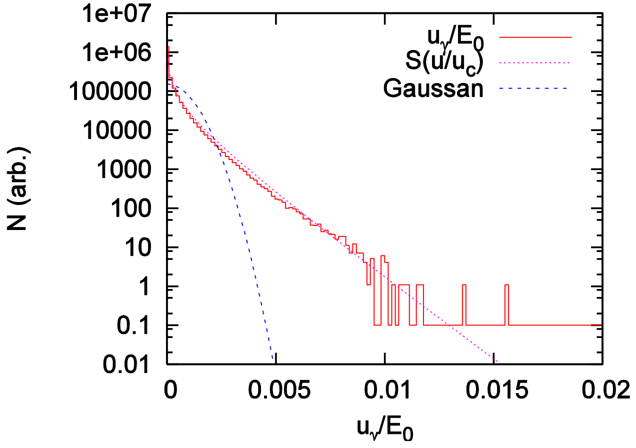
Beamstrahlung: essential for Higgs factory

- Synchrotron radiation during beam-beam collision
- Calculate trajectory interacting with colliding beam.
- Particles emit synchrotron radiation due to the momentum kick dp/ds.

ρ=23.5/19.7m<< ρ_{bend}= 6,094/11,000m (CEPC/TLEP)

u_c= 164/194 MeV, N_γ=0.21/0.092





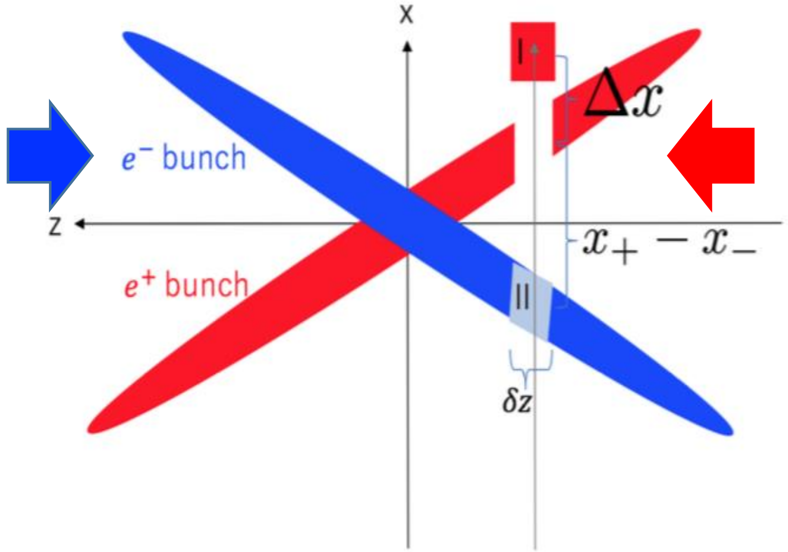
$$ds = \frac{z_i - z_{i+1}}{2} \qquad \langle\delta\rangle = dn_\gamma\langle u\rangle = \frac{2r_e\gamma^3}{3\rho^2}ds$$

$$\frac{1}{\rho_{x,y}} = \frac{dp_{x,y}}{ds} \qquad \langle\delta^2\rangle = dn_\gamma\langle u^2\rangle = \frac{55}{24\sqrt{3}}\frac{r_e\hbar\gamma^5}{mc\rho^3}ds$$

$$\frac{dn_\gamma(\omega)}{d\omega} = \frac{\sqrt{3}\alpha\gamma\Delta s}{2\pi\rho\omega_c}S(\frac{\omega}{\omega_c})$$

$$S(\xi) = \int_\xi^\infty K_{\frac{5}{3}}(y)dy$$

Coherent beam-beam instability in correlated head-tail mode



- Localized Cross wake field gives correlation of two colliding beam by convolution of each dipole moment.

$$\boxed{\Delta p_{x,\mp}(z_\mp)} = -\int_{-\infty}^{\infty} \boxed{W_x^{(\mp)}(z_\mp - z'_\pm)}\boxed{\rho_x^{(\pm)}(z'_\pm)}dz'_\pm$$

$$W_x^{(-)}(z) = -\frac{N^{(+)}r_e}{\gamma^{(-)}\bar{\sigma}_x^2}\left[1 - \frac{\sqrt{\pi}\theta_P z}{2\bar{\sigma}_z}\,\mathrm{Im}\; w\left(\frac{\theta_P z}{2\bar{\sigma}_z}\right)\right]$$

- Mode coupling theory for the localized cross wake force

$$x(J,\phi;t) = \sum_{l,k} x_{kl}(t)\sqrt{\frac{k!}{(|l|+k)!}}\hat{J}^{|l|/2}L_k^{(|l|)}(\hat{J})e^{il\phi}$$

$$M_{k\ell,k'\ell'} = \pm\frac{\beta_x}{2}i^{l-l'-1}\int_{-\infty}^{\infty} d\omega Z(\omega)g_{kl}(\omega)g_{k'l'}(\omega)$$

$$M_0 = e^{-2\pi i l\nu_s}\delta_{kk'}\delta_{ll'}\begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix}$$

$$M_W = \begin{pmatrix} 1 & 0 \\ -2M_{klk'l'} & 1. \end{pmatrix}$$

Transformations for (x_{kl}, p_{kl}).

Solve eigenvalue problem for M_0M_w.

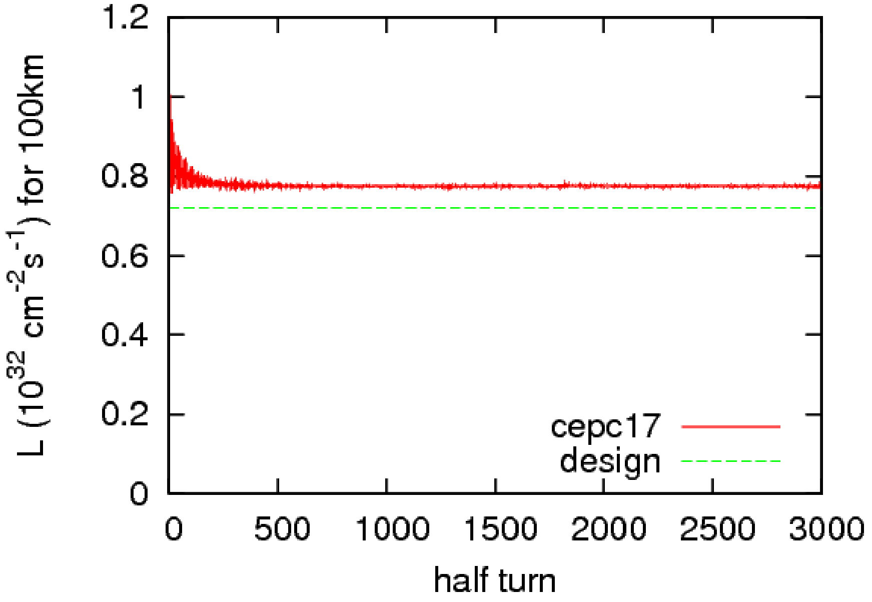
Beam-beam simulation, luminosity evaluation

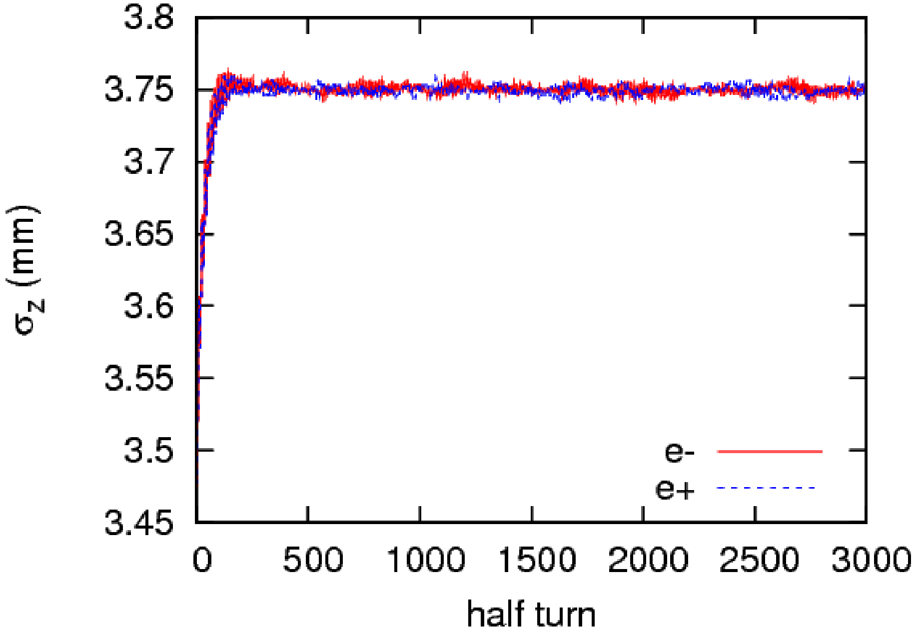
- Strong-strong simulation
- Each beam is represented by many macro-particles (10^6).
- Beam-beam force is calculated by solving Poisson equation for colliding beam distribution or by formula for fitted Gaussian distribution.
- Luminosity and beam sizes are calculated turn-by-turn.

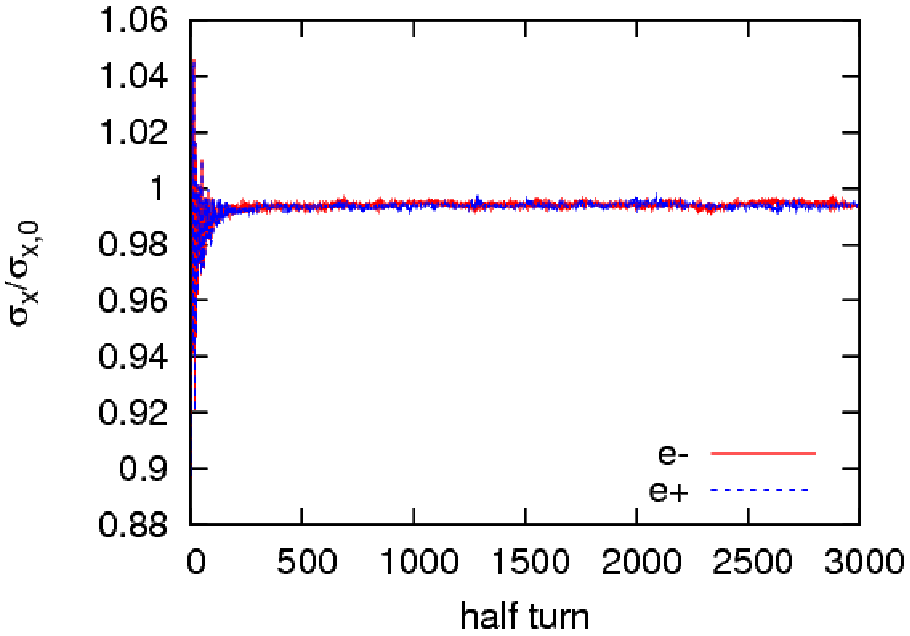
CEPC-H

Strong-strong simultion

- $L_{tot}=0.72\times10^{32}\times286=2.06\times10^{34}$ $cm^{-2}s^{-1}$~ design value.







Beam lifetime

- Beamstrahlung enhances non-Gaussian tail in energy distribution.
- Lifetime estimated by weak-strong and strong-strong simulations
- In equilibrium, particles escape a boundary is the same number as damping from the boundary. [M. Sands, SLAC-R-121 (1970)]

$$\frac{dN}{dt} = f(J_i)\frac{dJ_i}{dt}$$

$$\frac{dJ_i}{dt} = -\frac{2J_i}{\tau_i}$$

$$\tau_\ell = \frac{N}{\frac{dN}{dt}} = \frac{t_i}{2J_{i,max}f(J_{i,max})}$$

f(J): equilibrium beam distribution.
For example f(J)=exp(-J/ε) for Gaussian.
Now f(J) is given numerically by beam-beam simulation.

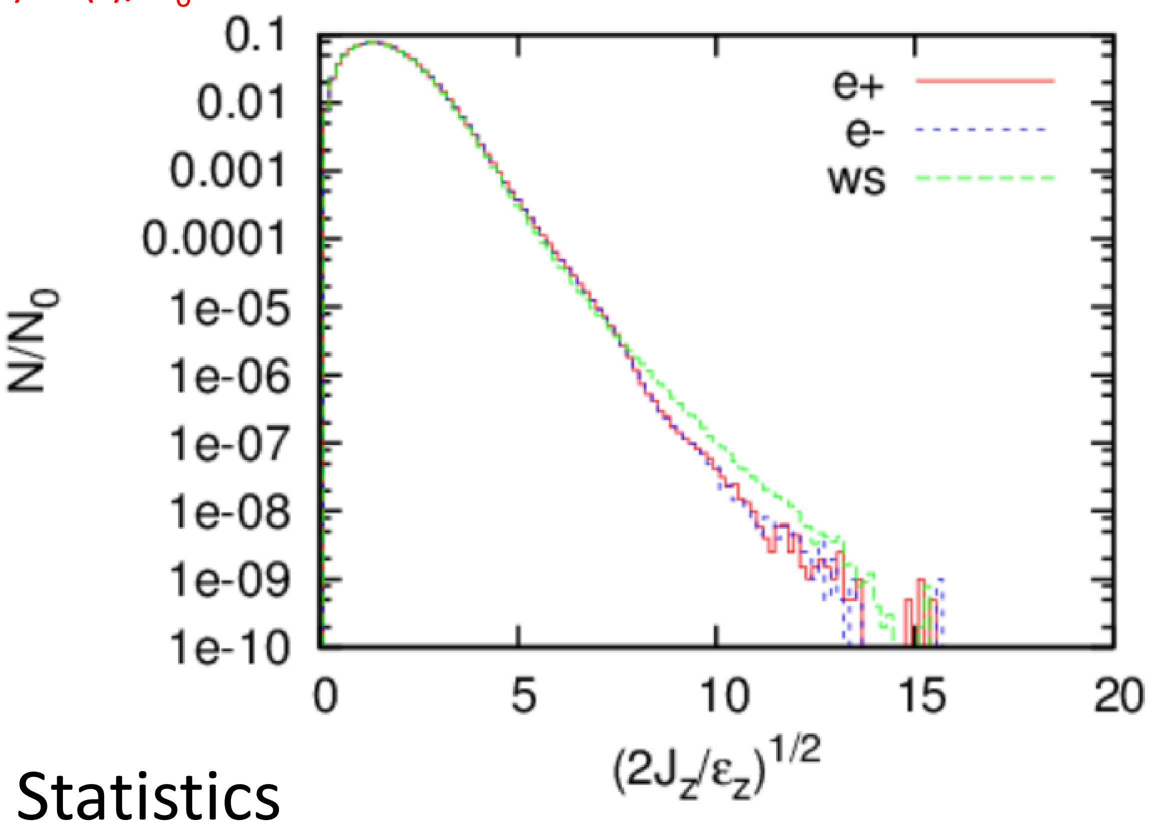
We focus longitudinal distribution, i=z.

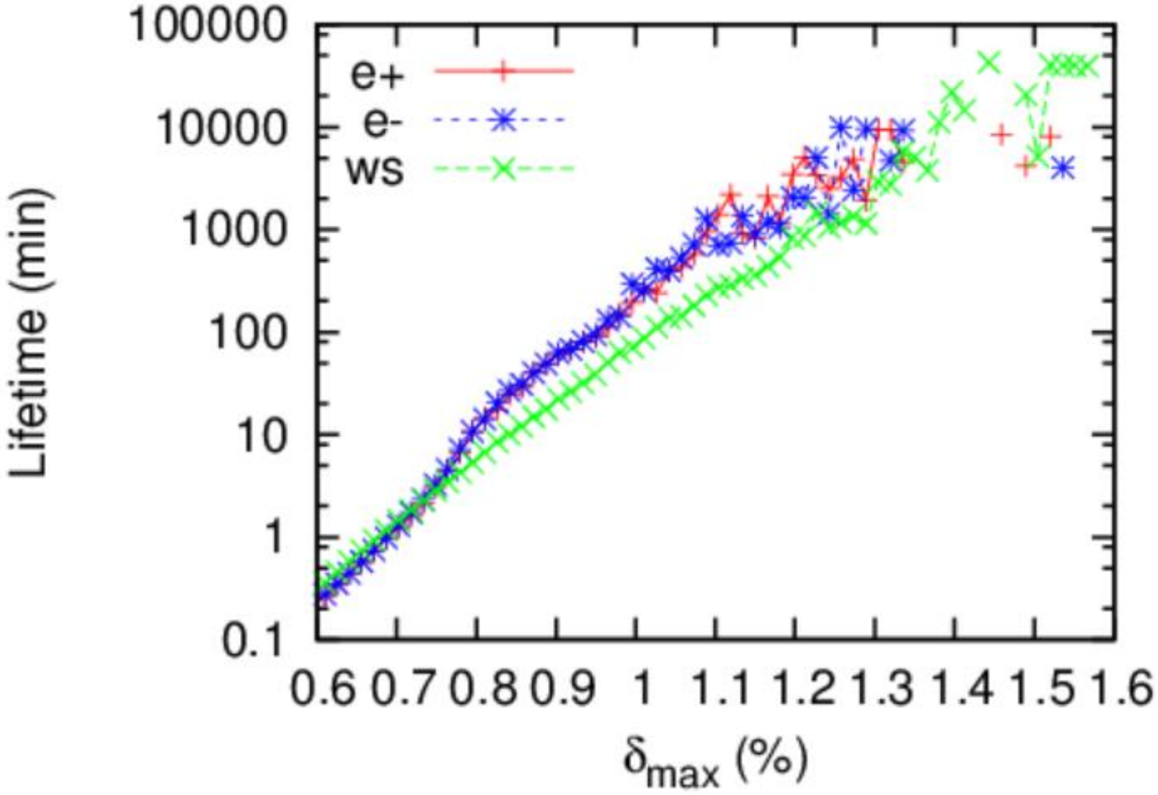
Beam tail distribution and life in longitudinal

Jz distribution

Life time

$f(J)=N(J)/N_0$





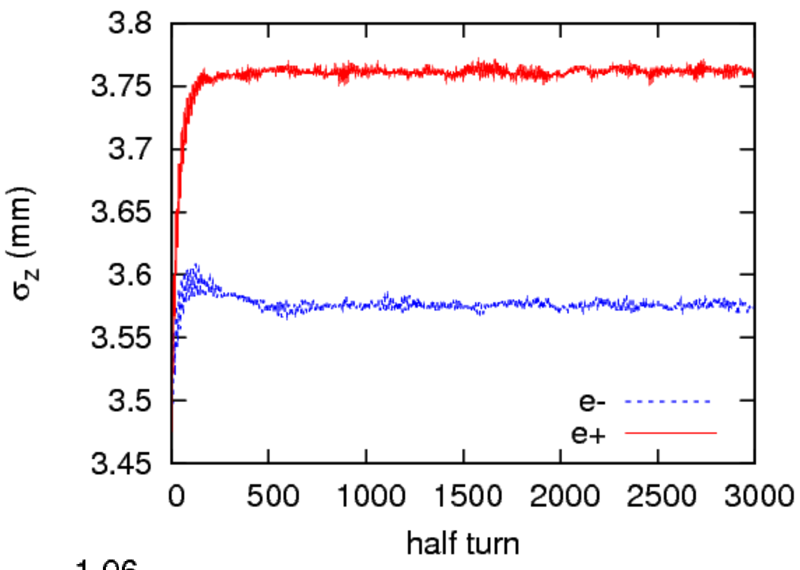
Statistics

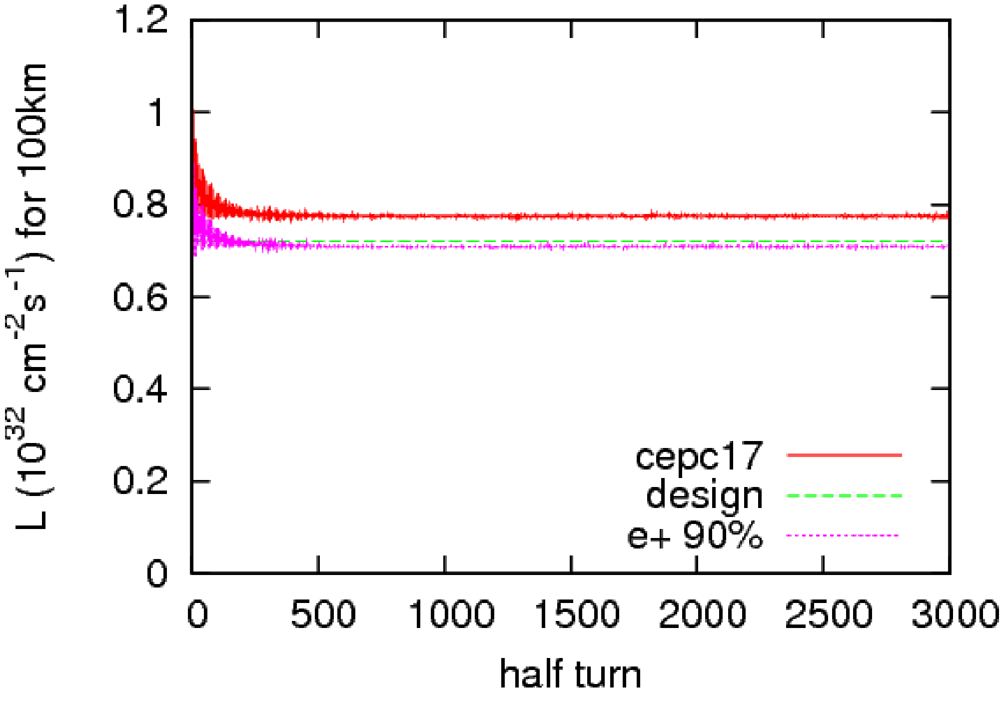
Accumulate 1000-3000 turns, $N_p=10^6$, N_pTurn$=2\times10^9$ (StrongStrong)

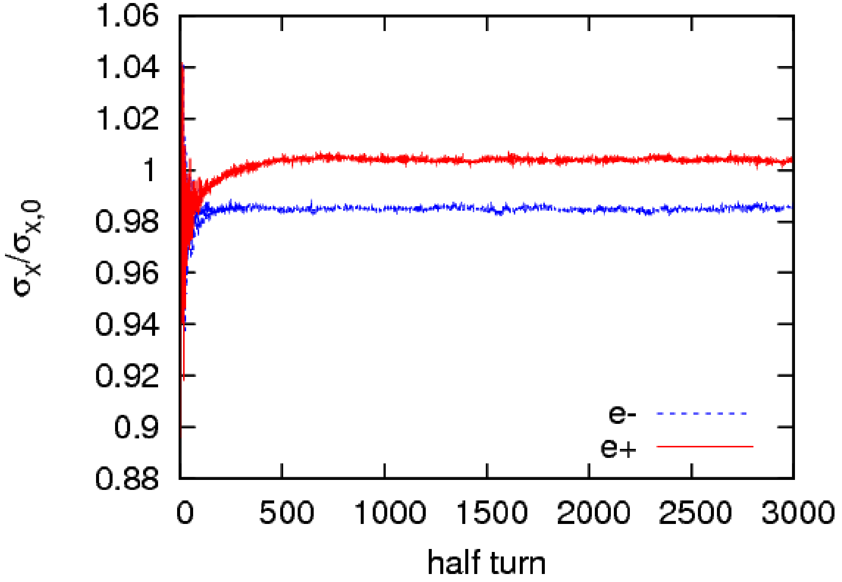
10^8 turns, $N_p=10^2$, N_pTurn$=10^{10}$ (WeakStrong)

Beam current asymmetry, L/bunch and $\sigma_{z,x}$

- e+: 90% e-:100%
- $\sigma_{z,x,y}$ (e-)<$\sigma_{z,x,y}$ (e+)
- Stable condition exists for the 10% current asymmetry.

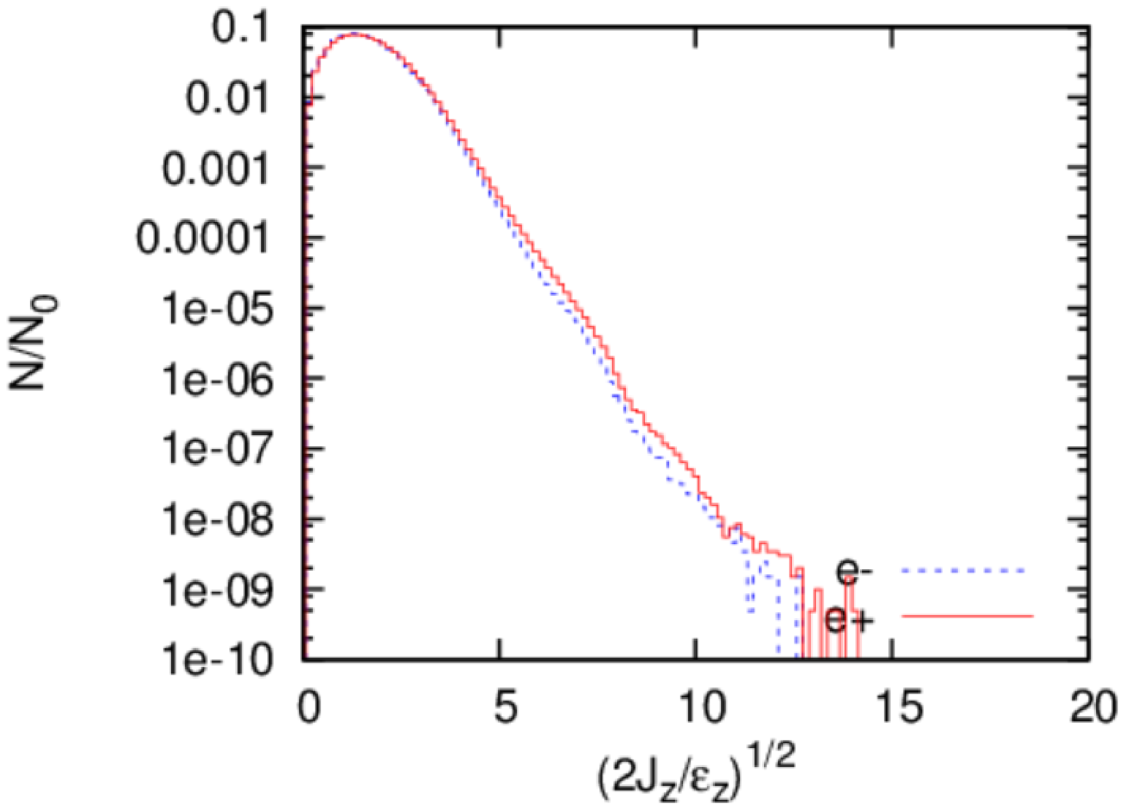


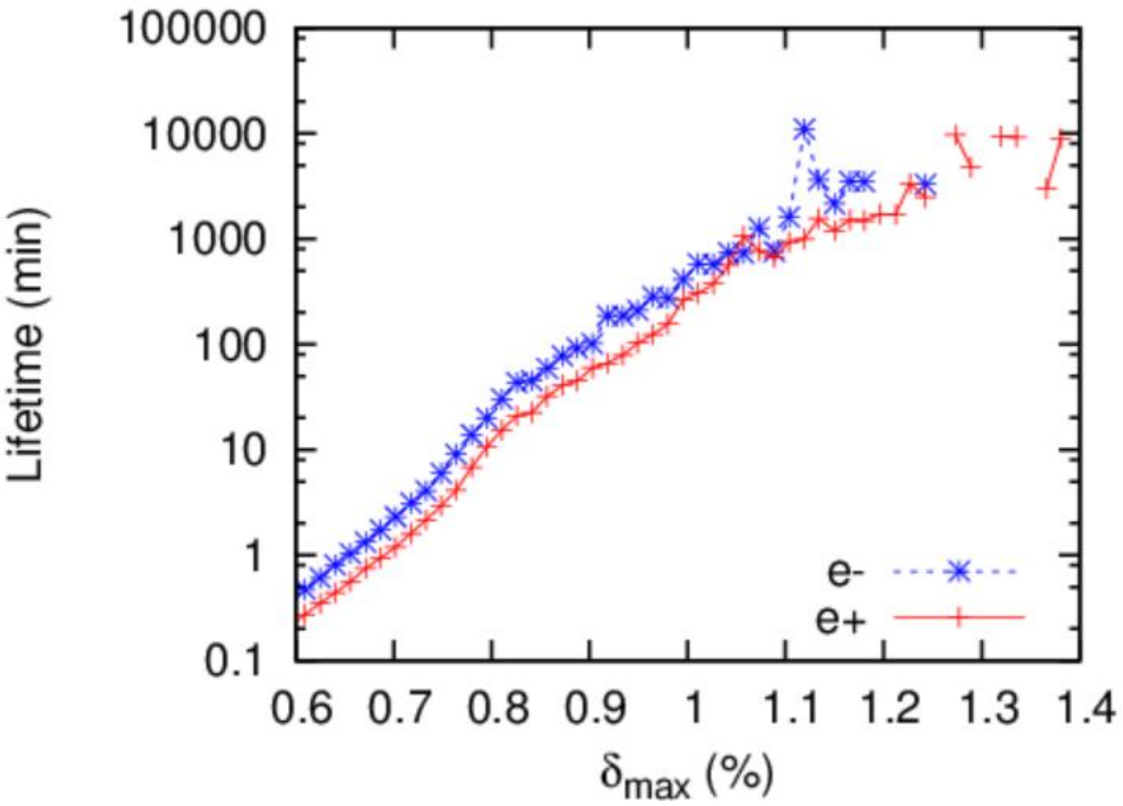




Beam current asymmetry, lifetime

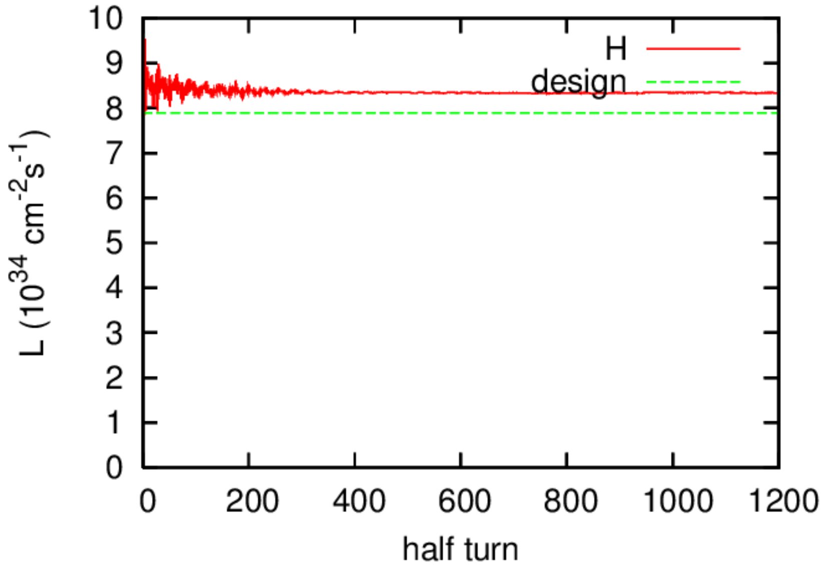
- e+: 90% e-:100%

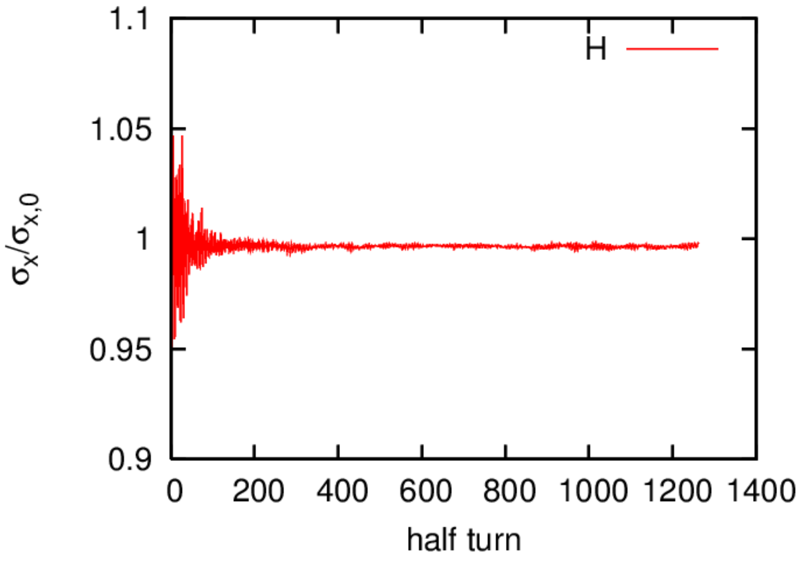


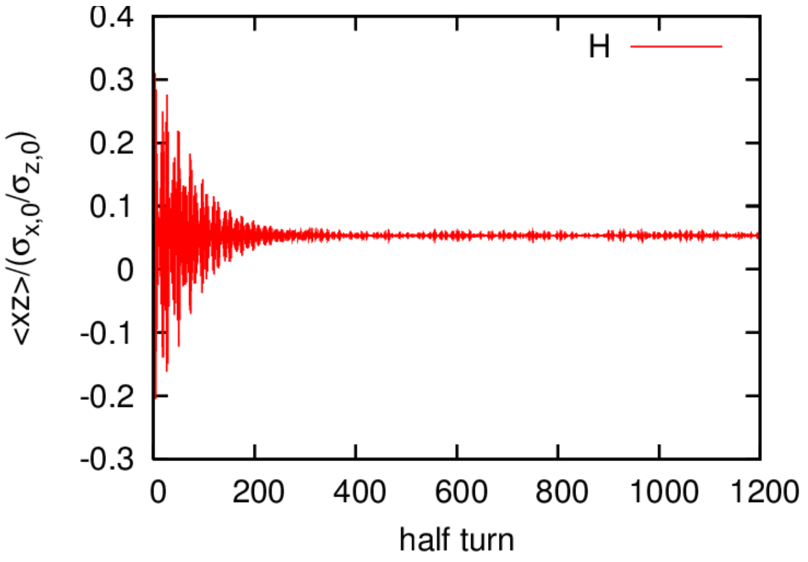


Strong-strong simulation-FCCee-H

- L is slightly higher than the design
- Coherent motion in <xz> damps smoothly, no residual effects.
- Horizontal beam size is the same as the design.

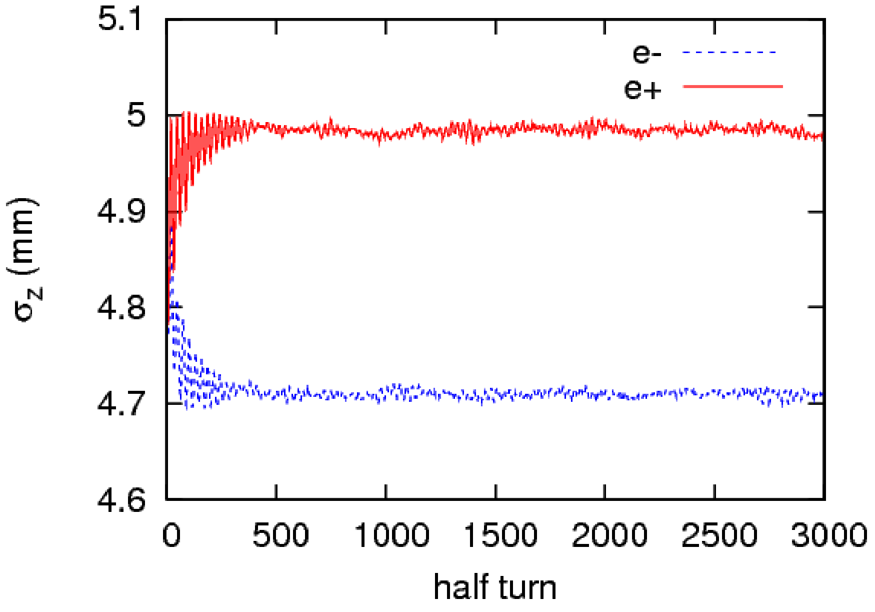


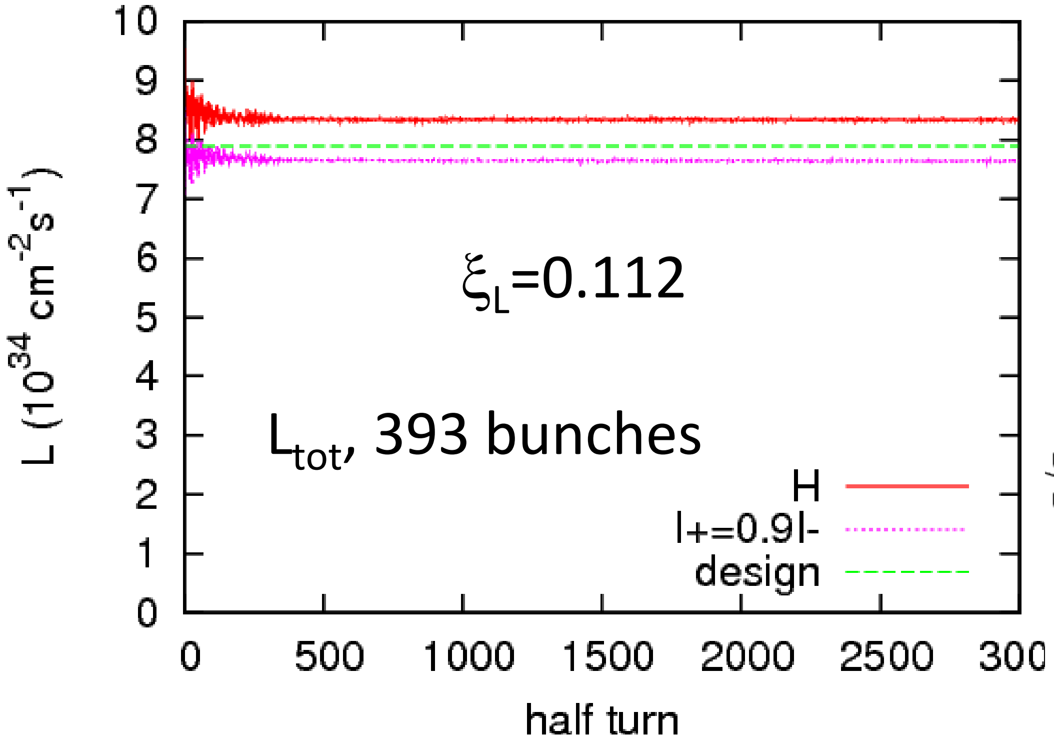


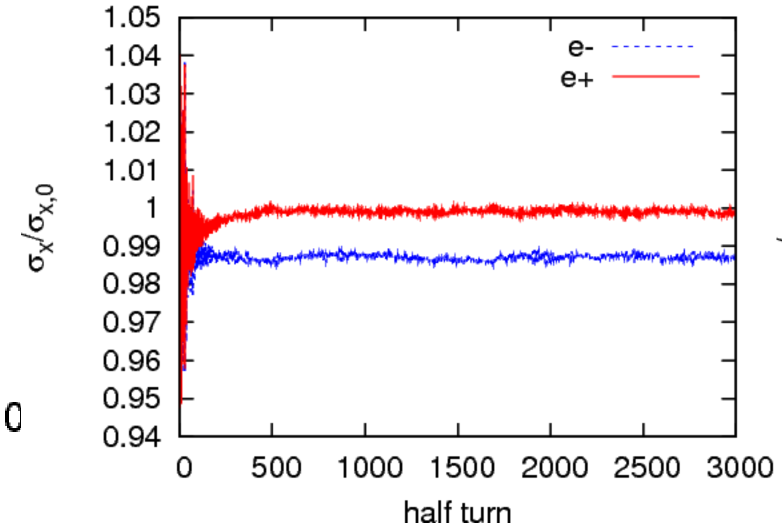


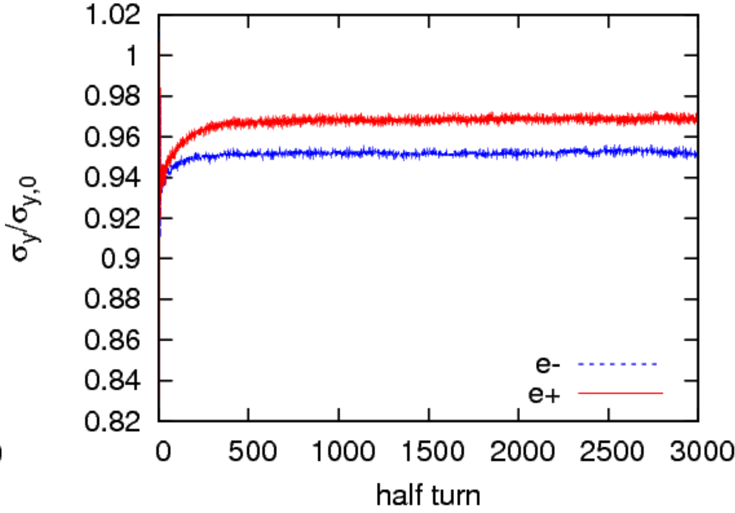
FCCee-H

- There is no problem for 10% current asymmetry (90% e+)



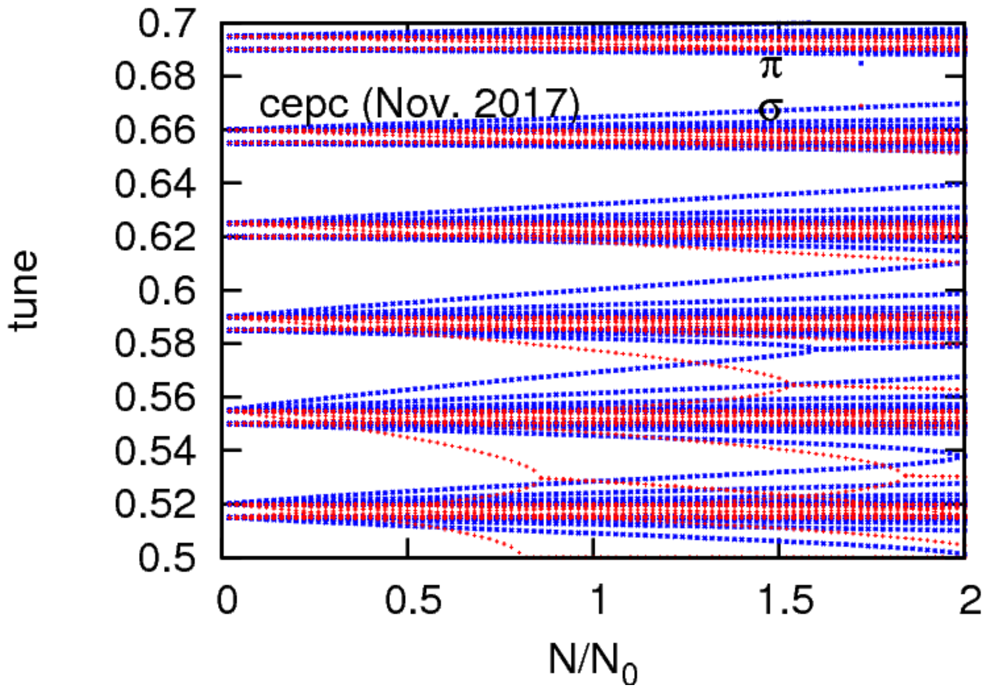


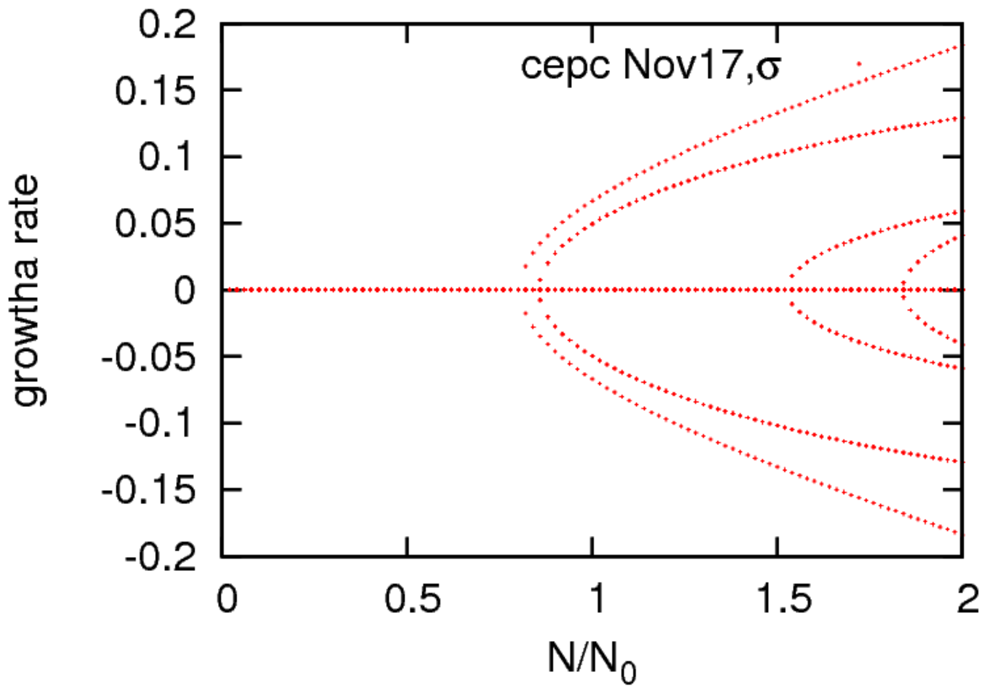




Coherent beam-beam instability in CEPC-H

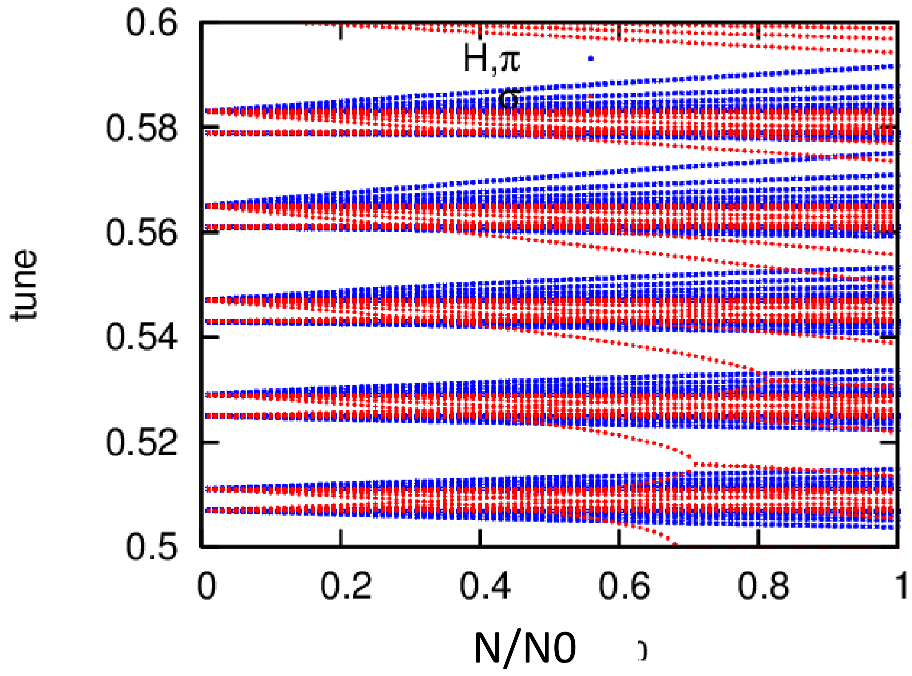
- N_0: design bunch population
- Threshold is 80% of the design current.
- No signal in the strong-strong beam-beam simulation.

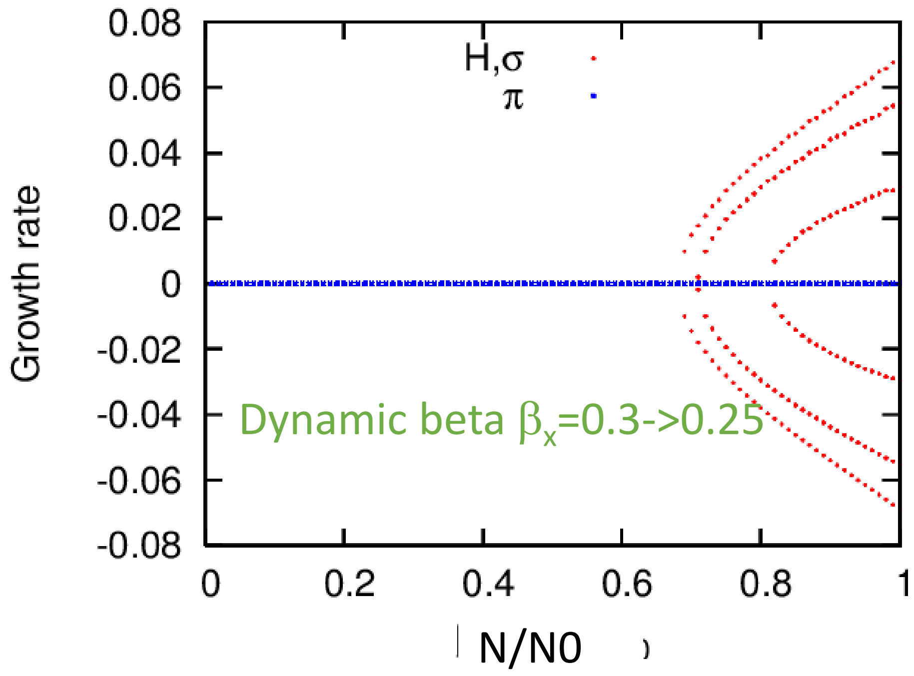




FCCee-H

- N_0: design bunch population
- Threshold is 80% of the design current.
- No signal in the strong-strong beam-beam simulation.
- Dynamic beta effect squeezes β_x=0.3m to 0.25m may suppress the instability.





Summary for H factories

- Luminosity is $2x10^{34}$ and $8x10^{34}$ $cm^{-2}s^{-1}$ for CEPC-H and FCCee-H. The difference is due to beta (1:2) and beam current (1:2). Simulations showed the luminosities of H's were feasible.
- Threshold of coherent beam-beam head-tail instability is around 0.7-0.8 for both H's. No clear effect is seen. Perhaps fast damping rate and/or dynamic beta suppress the instability. The instability was seen in old FCCee-H parameters (PRL).

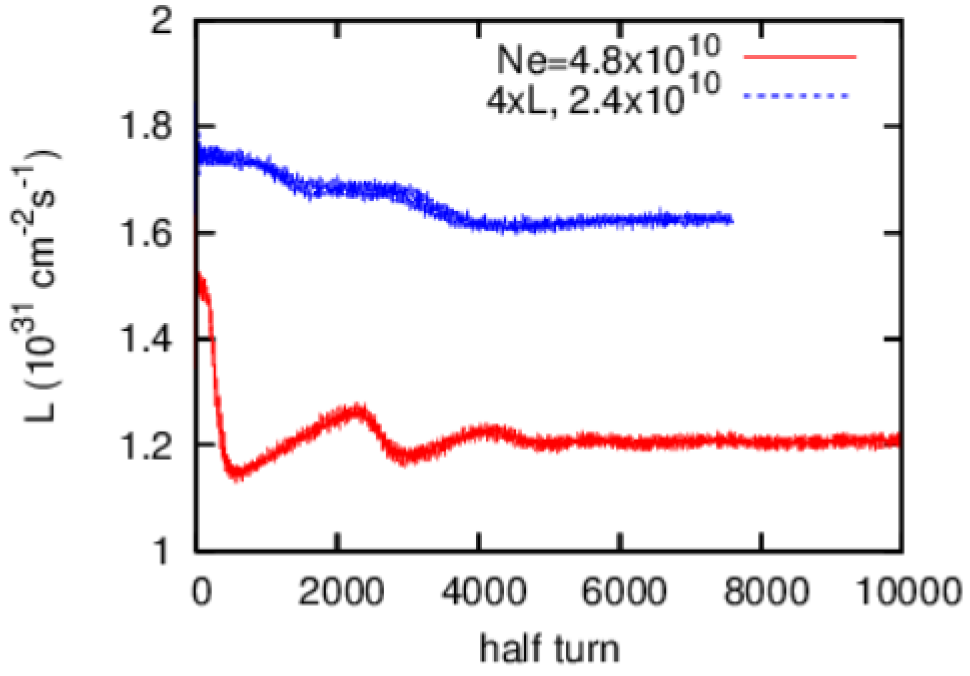
CEPC-Z

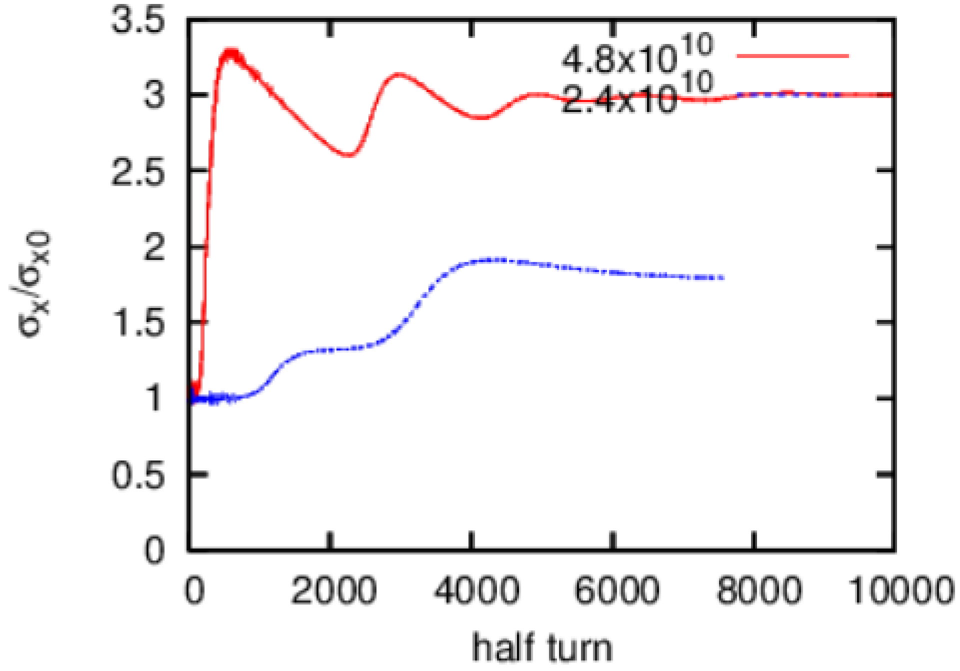
- In the early design, the luminosity is 10^{34} $cm^{-1}s^{-1}$ and the beam-beam tune shift is very small ξ_y=0.016.
- It seems there is room to increase luminosity and tune shift, 9x and 3x.
- Beam-beam simulation for ξ_y=0.024 and 0.048, L=2.2 and $9x10^{34}cm^{-2}s^{1}$ were performed.

Luminosity and horizontal beam size

- Strong-strong using Gaussian fit

Parameters at Nov 2017.

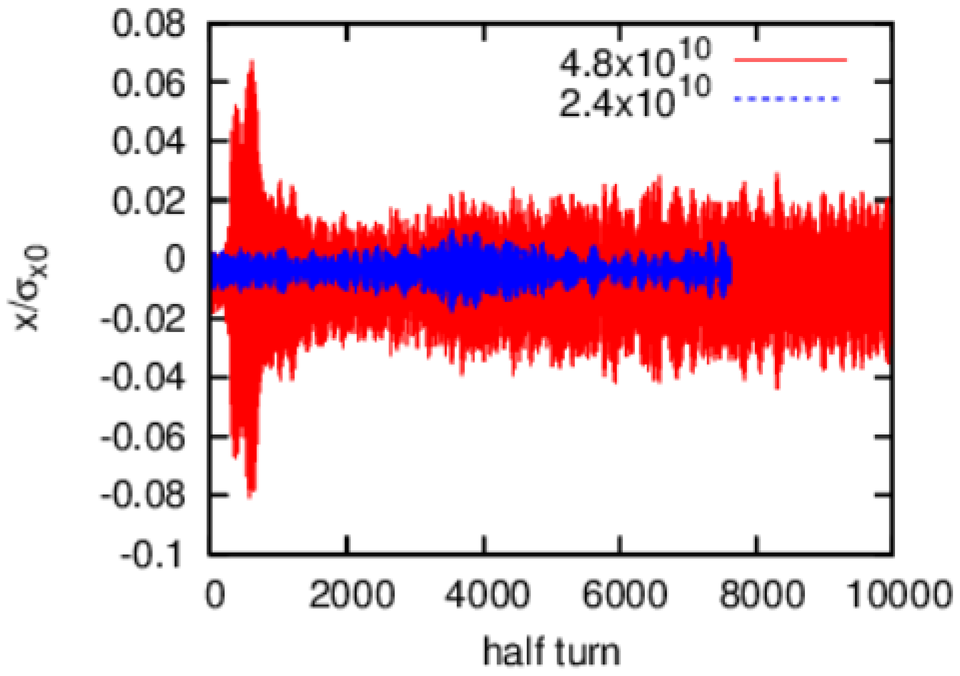


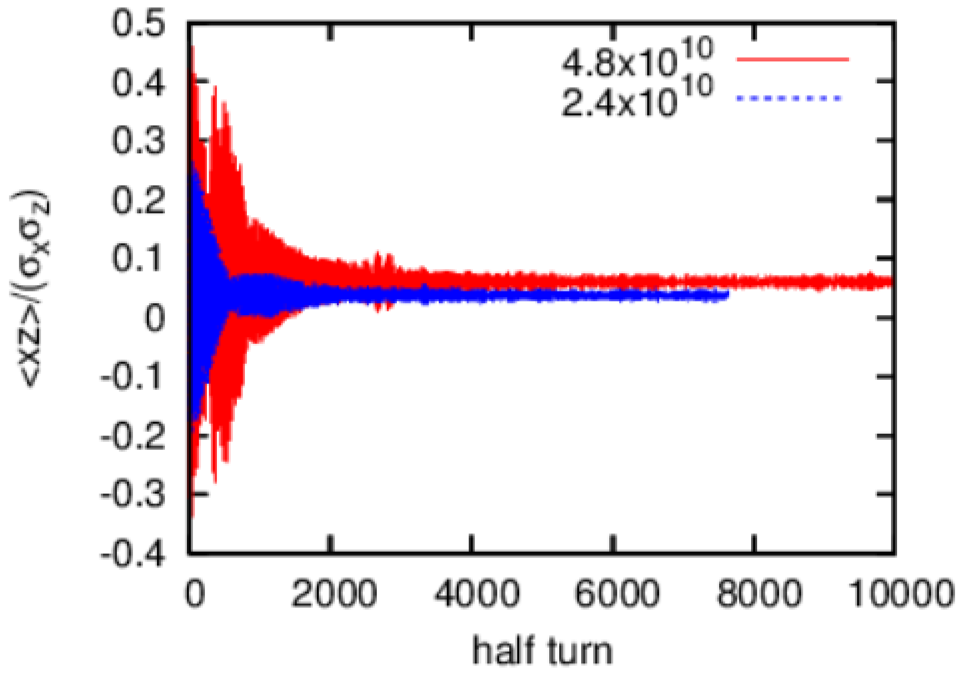


Coherent motion

- x

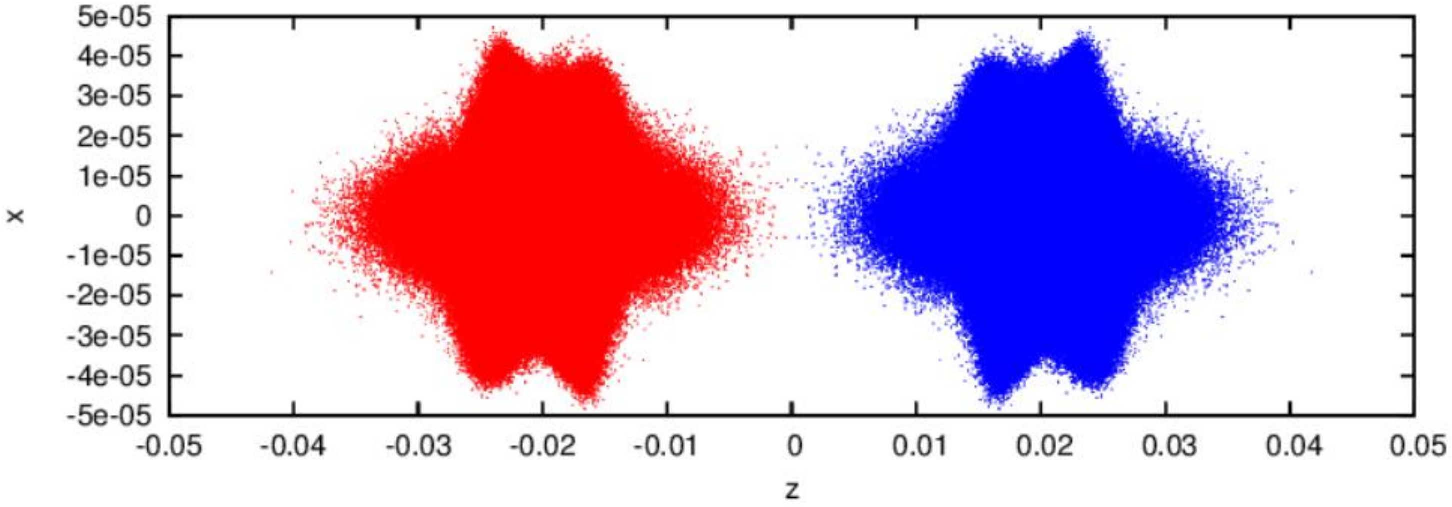
<xz>





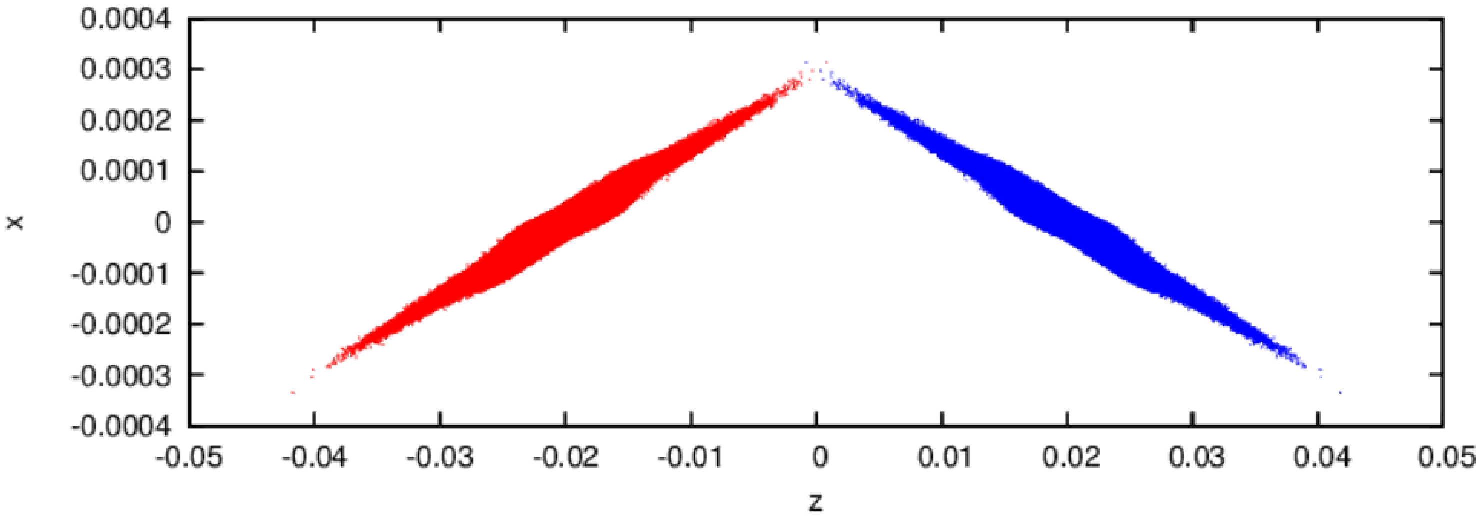
- Higher order mode is hard to see in <xz>.

x-z distribution after 300 turns Ne=4.8×10^{10}.



L>=2 mode is seen.

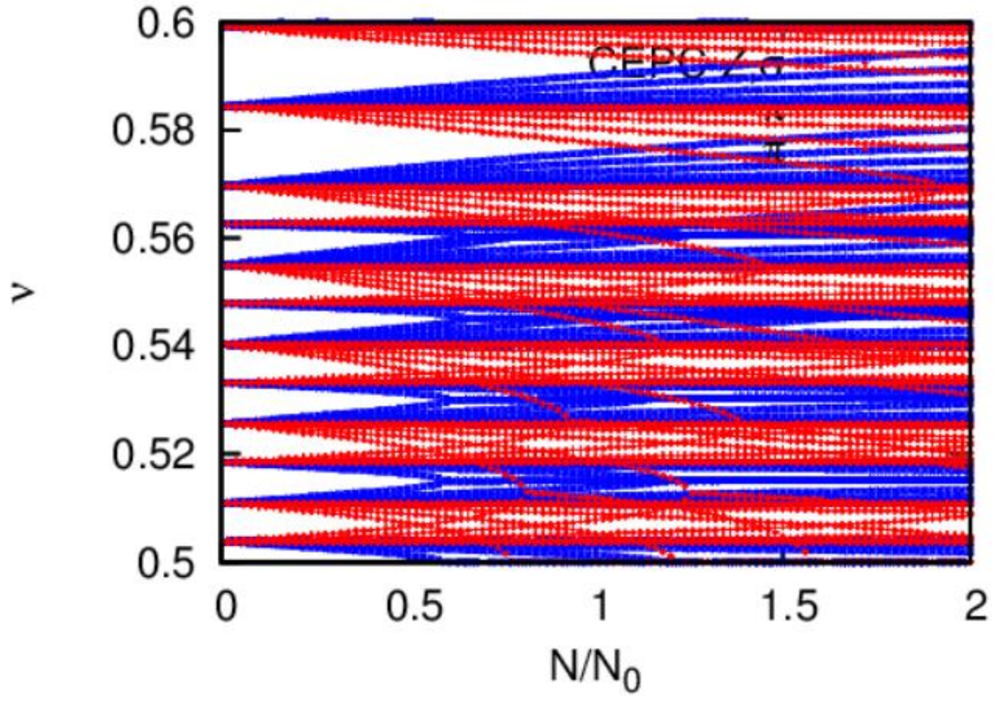
Crossing tilt is removed in this plot.



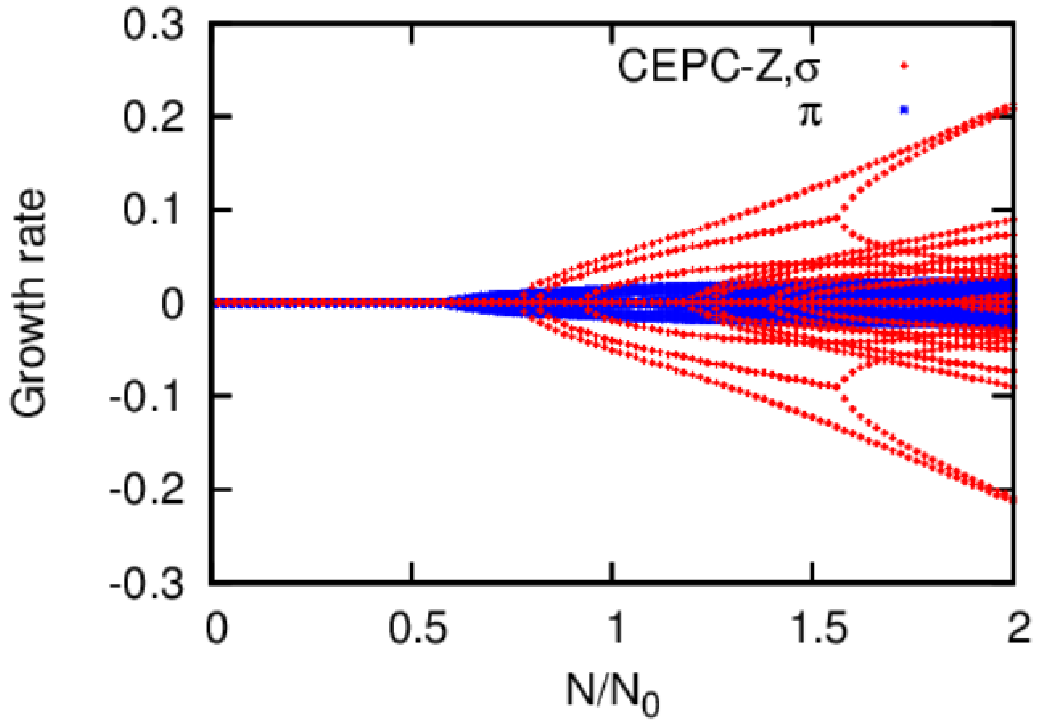
Crossing tilt is taken into account.

CEPC-Z Eigen mode analysis, ξ_x=0.0094, θ_P=12

- Tune



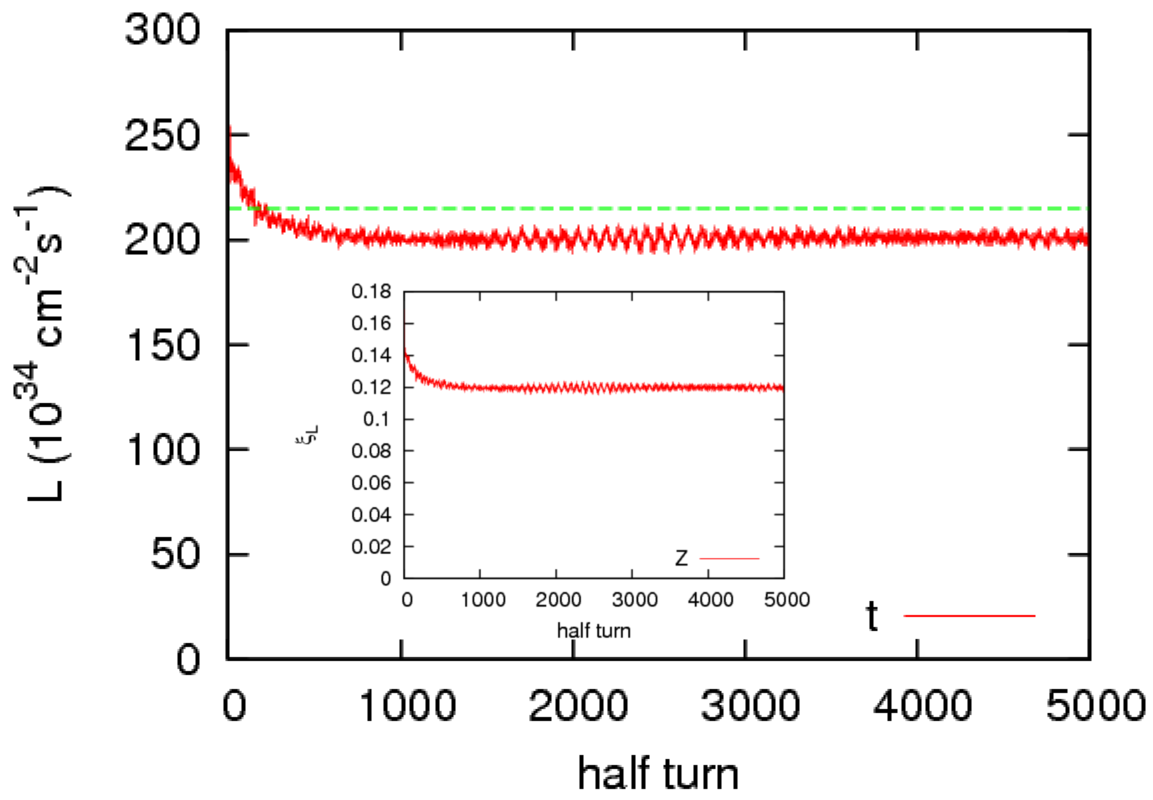
Growth rate



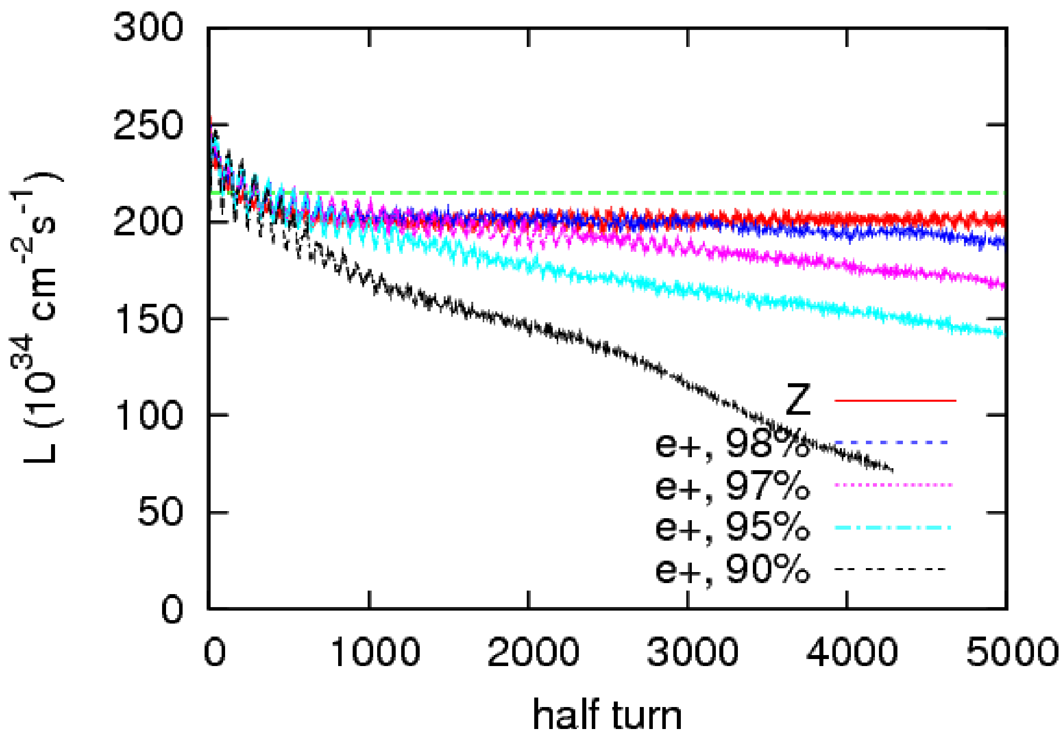
- Threshold, N=0.6N_0.

FCCee-Z

- Early design of FCCee-Z suffered the coherent beam-beam instability.
- β_x^* was squeezed, Piwinski angle was increased and tune x was optimized. (D. Shatilov and K. Oide)
- $L=2\times10^{36}\ cm^{-2}s^{-1}$ is achieved in simulations



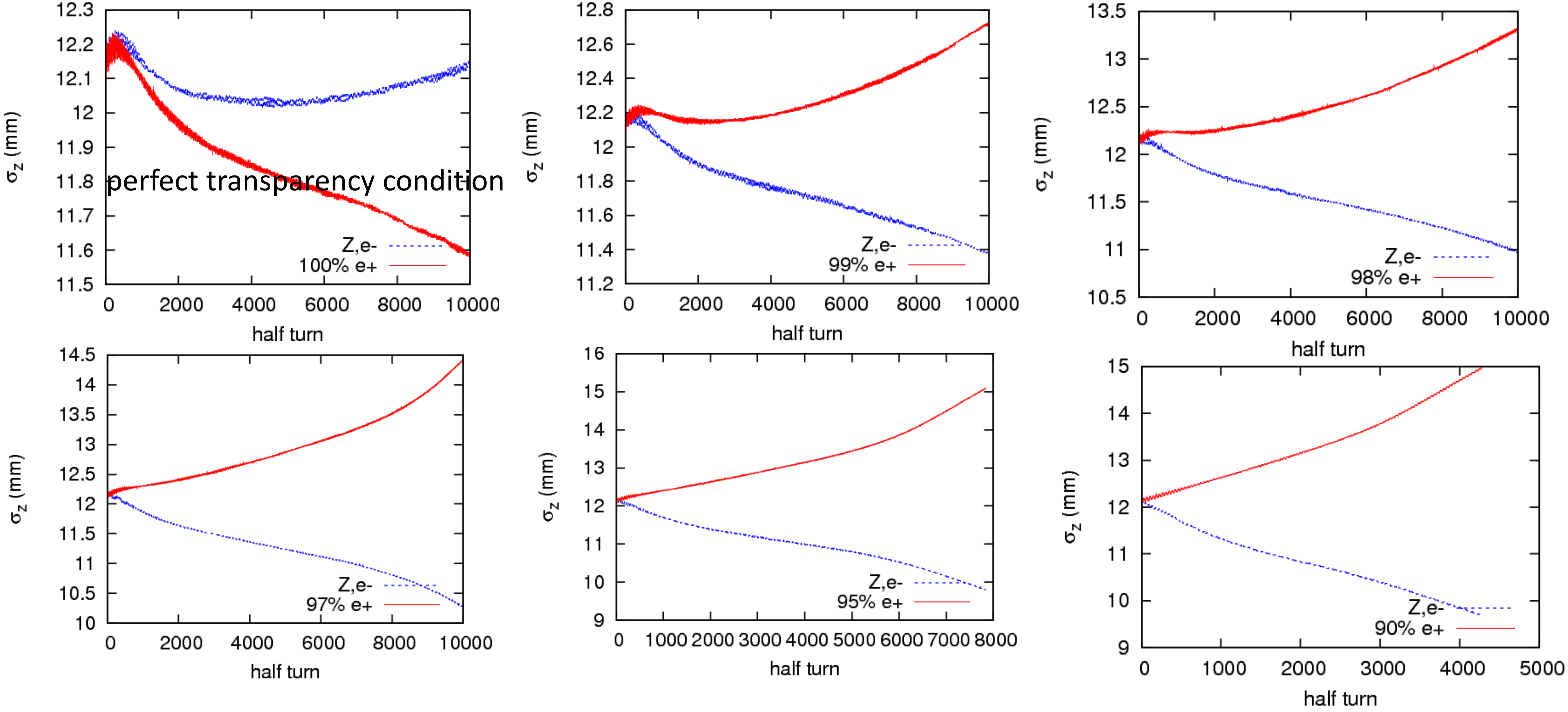
Flip flop is very strong noted by D. Shatilov



- Beam-beam simulation with current asymmetry.
- Luminosity degrade is seen even asymmetry of 2% (98%e+) . It is hard to maintain the asymmetry <2%.
- D. Shatilov said 5% asymmetry was acceptable by his code Lifetrack using Bootstrap (preset σ_z for Beamstrahlung).

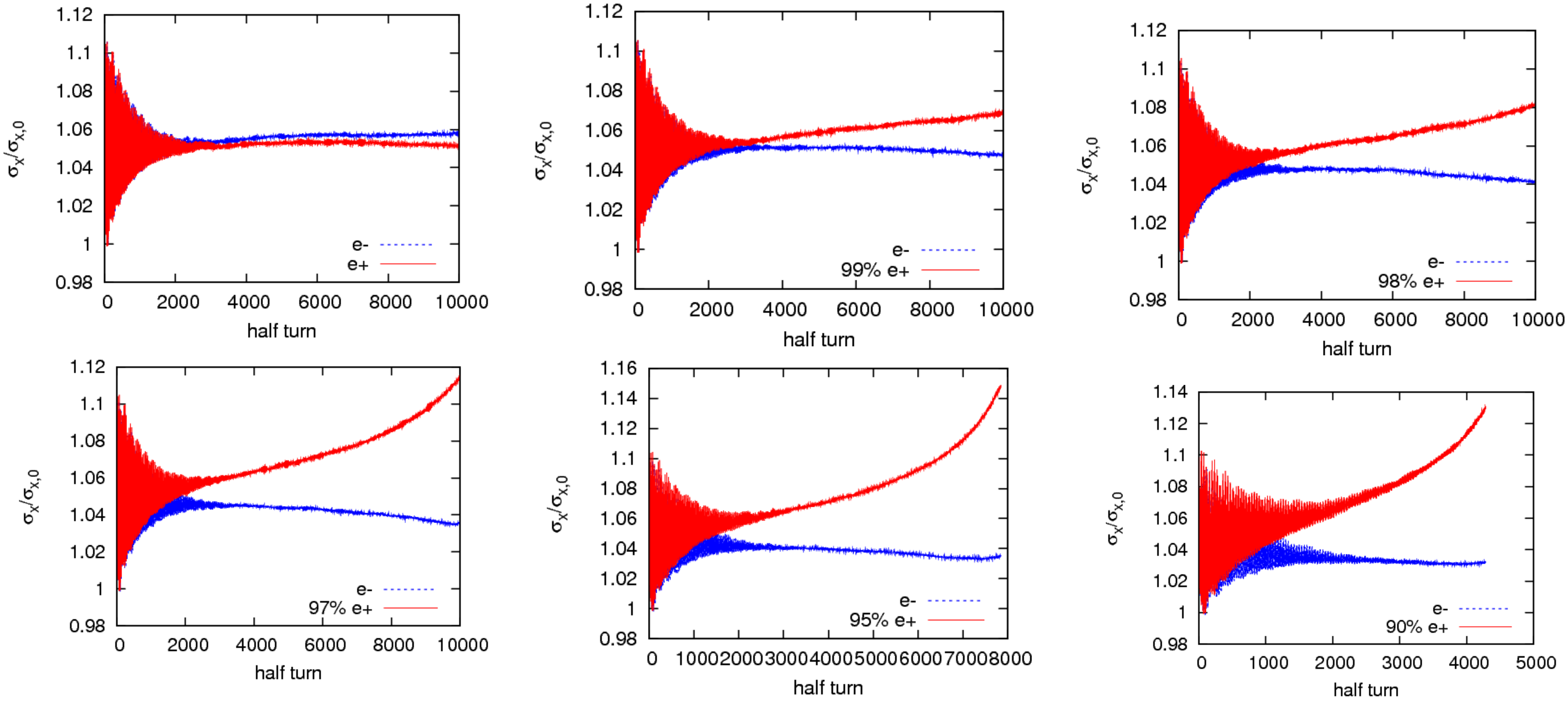
Bunch length

σ_z asymmetry appears even in the perfect transparency condition. Preset σ_z=12.1mm

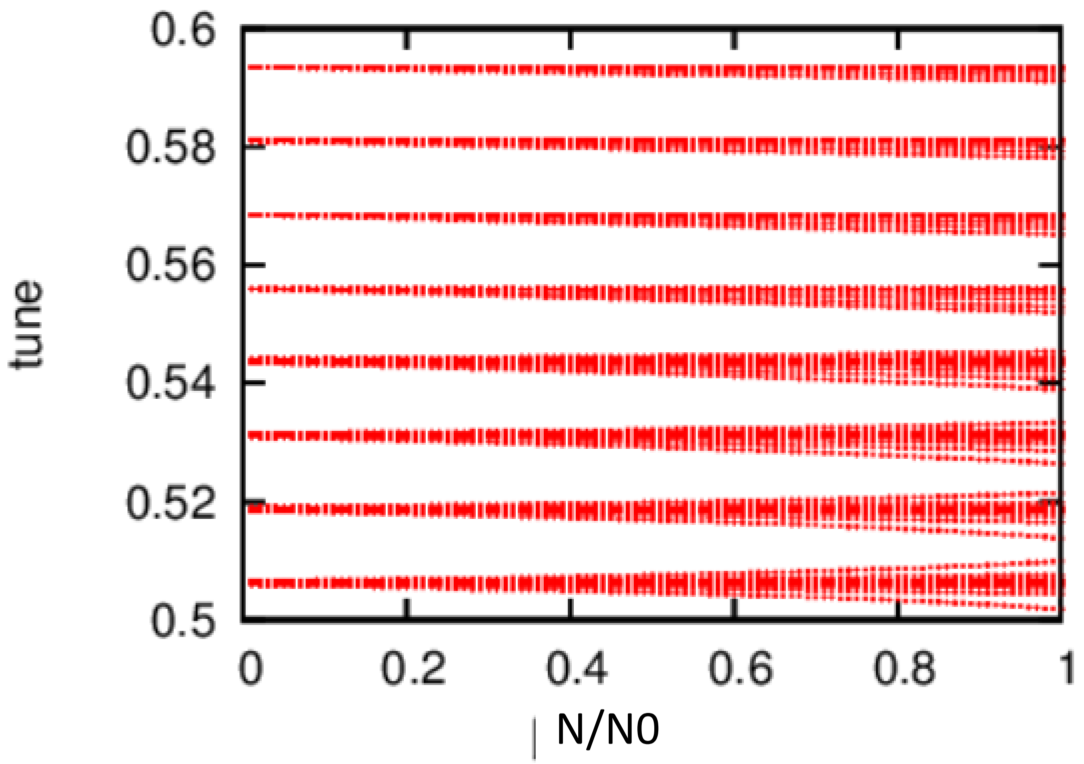


Horizontal beam size

Perhaps, change of σ_z enhances the coherent beam-beam instability. Need to check.



Eigen mode analysis for FCCee-Z (Aug. 17)



- Stable at the design current, but close to the threshold.

Summary for Z

- CEPC-Z Ne=2.4-4.8x10^{10} (ξ_y=0.024-0.048), coherent head-tail beam-beam instability has been seen.
- The threshold is 0.6-0.7 times of the design bunch population.
- Coherent instability in σ_x was seen, because of L=2 mode.
- Parameter tuning, decreases β_x 0.36->0.2m and/or the bunch population 4.8->4e10. Then the instability is cured now.

- FCCee-Z (ξy=0.133) seems stable for the coherent instability at the design current.
- The bunch length related to beamstrahlung is too sensitive for current asymmetry. Even equal current, bunch length asymmetry occurs.
- Horizontal beam size increases for increasing bunch length asymmetry.

Electron cloud instability in Z

Z (45.5GeV) Higgs (120GeV)

	CEPC-Z	FCCee-Z	CEPC-H	FCCee-H
ε_x(nm)/ ε_y (pm)	0.17/2.9	0.27/1.0	1.21/3.6	0.63/1.3
β_x/ β_y (mm)	360/2	150/0.8	360/2	300/1
σ_z(mm)/$\sigma_{z,BS}$(mm)	3.67/5.18	3.5/12.1	2.72/3.48	3.15/4.9
θ(mrad), θ_P	0.0165, 10.8	0.015, 28.5	0.0165,2.75	0.015, 5.3
N_e	1.6-4.8x10^{10}	17x10^{10}	12.9x10^{10}	15x10^{10}
N_{bunch}, t_{sp} (ns)	10900, 35	16640, 20	286	393
L_{tot} ($cm^{-2}s^{-1}$)	1-9	230	2.0	7.8
ξ_x/ ξ_y	0.005-0.015/ 0.0165-0.048	0.004/0.133	0.024,0.094	0.016/0.108

Electron production

- Number of photon emitted by an positron E=45.5GeV

$$N_\gamma = \frac{5\pi}{\sqrt{3}} \frac{\alpha\gamma}{C} \qquad \alpha = \frac{1}{137}$$

- N_γ=0.06m^{-1} (, C=100km)
- PEY=0.1 (number of electron produced by a photon)
- N_{pe}=0.006 m^{-1}. (number of electron produced by a positron)

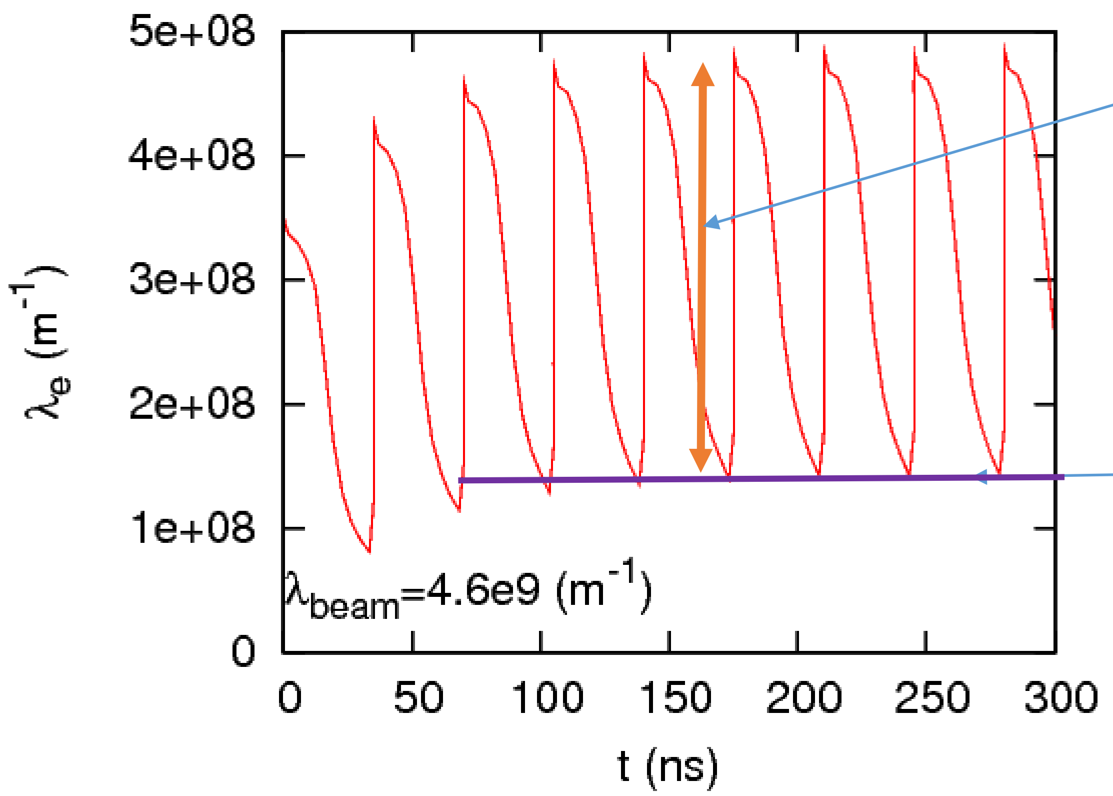
CEPC-Z & FCCee-Z

- N_b=4.8e10 & 17e10 , bunch spacing 35 ns & 20 ns
- The number of electron produced by an e^+ bunch

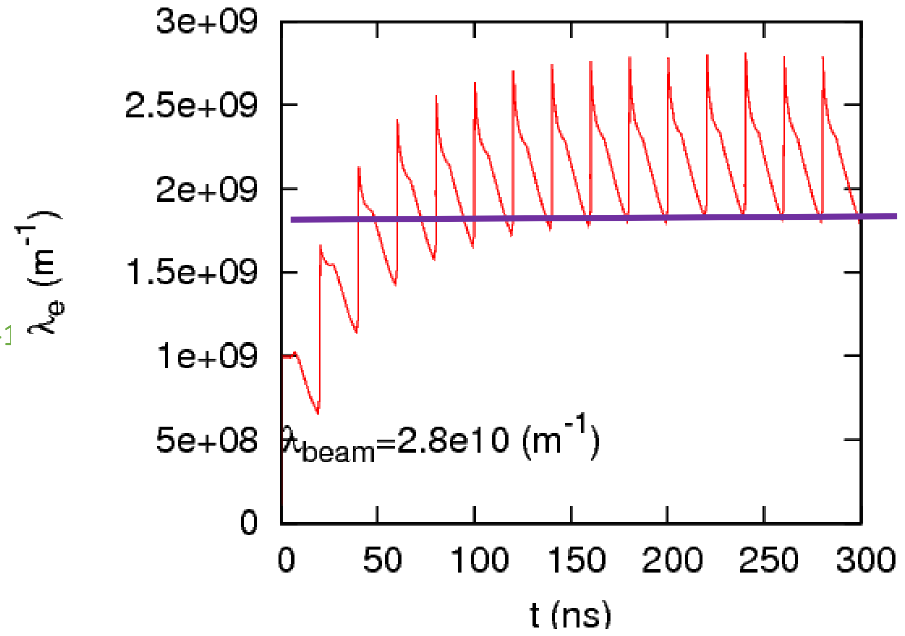
  $N_{pe} N_b$=$2.9\text{x}10^8$ m^{-1} & $1.0\text{x}10^9$ m^{-1}
- Beam line density, λ_b=$4.6\text{x}10^9$ m^{-1} & $2.8\text{x}10^{10}$ m^{-1}

Electron cloud density in drift space

- Chamber r=3cm cylindrical.



~2.9x10^8 m^{-1}

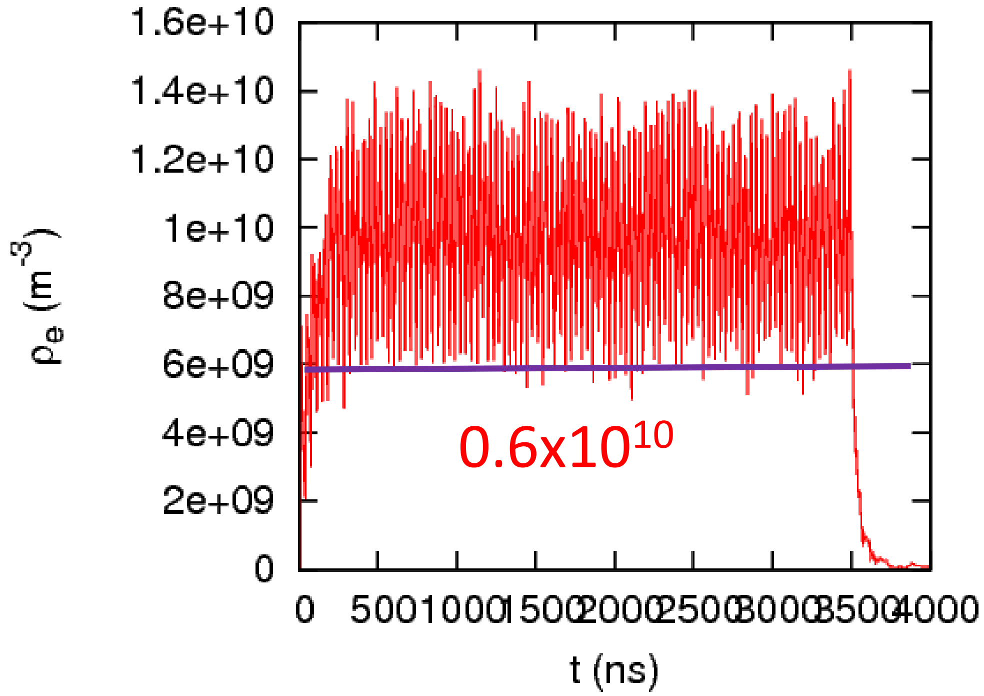


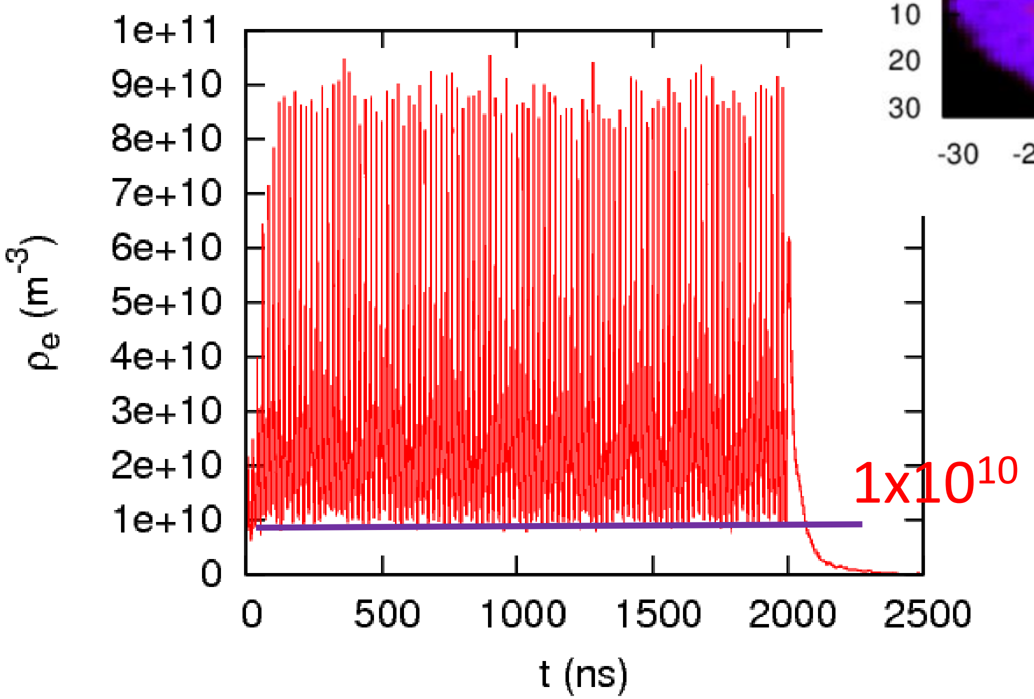
Electron line density when next bunch arrives

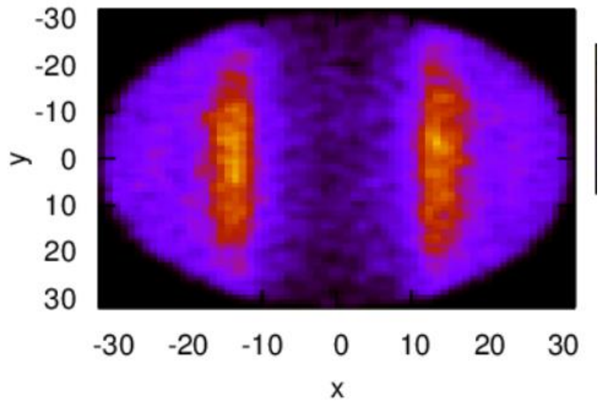
$\rho_e = 1.4\times10^8/0.0033 = 4\times10^{10}\ m^{-3}$.

Electron cloud density in bending magnet

- Direct emitted photon create electrons at the side of chamber. The electrons do not come to the chamber center.
- Synchrotron radiation reflected. Assume 10% of primary photon hit wall uniformly.



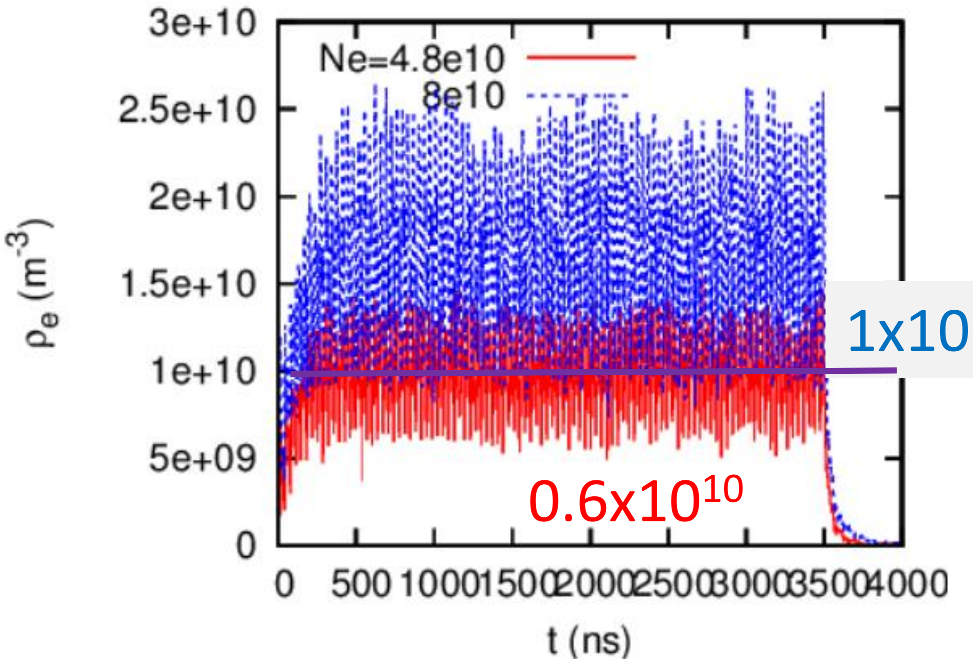


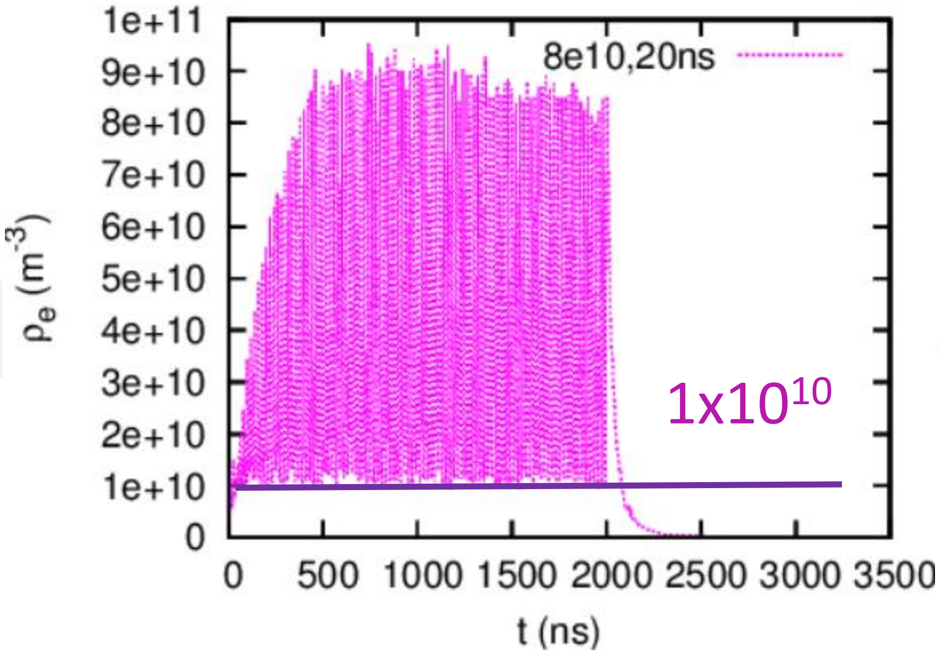


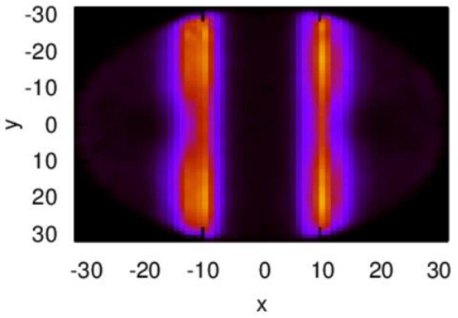
Other parameter cases

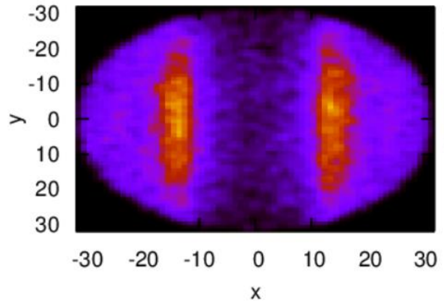
- Np=8e10, tsp=35ns

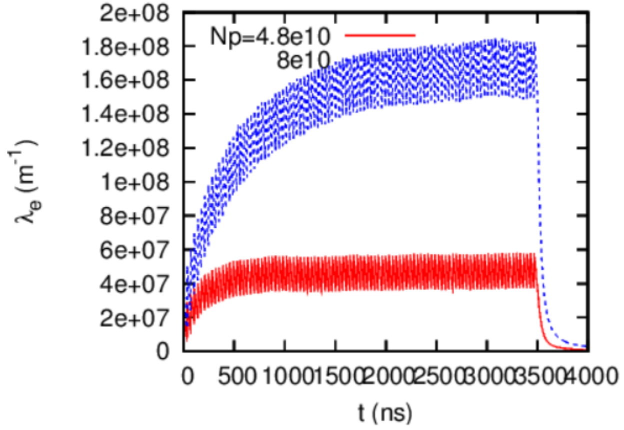
Np=8e10, 20ns

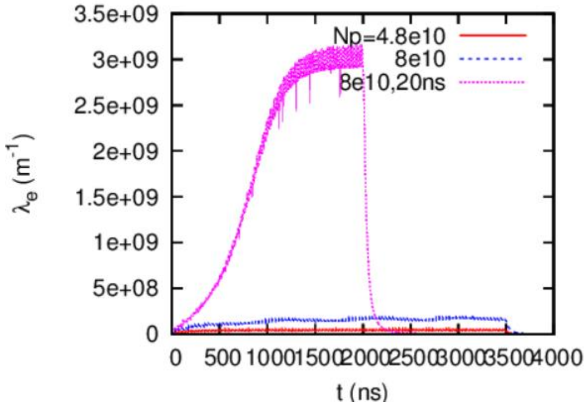












Central density does not increase so much compare with the line density.
Coupled bunch instability may occur.

Threshold density for single bunch electron cloud instability

- Electron oscillation inside a positron bunch

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}} \qquad \lambda_p = N_p/(\sqrt{2\pi}\sigma_z)$$

Positron line density

$\omega_e\sigma_z/c$=13.6, $\beta_x=\beta_y$=50m, σ_z=4.33mm,Np=4.8e10

$\omega_e\sigma_z/c$=17.6 $\beta_x=\beta_y$=50m, σ_z=4.33mm,Np=8.e10

$\omega_e\sigma_z/c$=36.6, $\beta_x=\beta_y$=50m, σ_z=12.1mm,Np=17.e10

- Threshold

$$\rho_{e,th} = \frac{2\gamma\nu_z\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L}$$

$\rho_{e,th}=2.9\times10^{10}$ m^{-3} ρ_e(drift)=5×10^{10} m^{-3} ρ_e(bend)=0.6×10^{10} m^{-3}. 4.8e10

$\rho_{e,th}=2.9\times10^{10}$ m^{-3} ρ_e(drift)= 7×10^{10}m^{-3} ρ_e(bend)= 1×10^{10} m^{-3}. 8e10, 35ns & 20ns

$\rho_{e,th}=1.87\times10^{10}$ m^{-3}. ρ_e(drift)=5.5×10^{10} m^{-3} ρ_e(bend)=1×10^{10} m^{-3}. 17e10

Summary for electron cloud effects

- Electron cloud build up for CEPC-Z, FCCee-Z have been studied.
- Area w/wo bending magnet is 6/1. Normal cell consists of 60m bend and 10m drift
- CEPC 4.8e10, 35ns $\rho_{e,ave}$=5/7+0.6*6/7=1.2x10^{10} cm^{-3}.
- 8e10 , 35ns $\rho_{e,ave}$=7/7+1*6/7=1.86x10^{10} cm^{-3}.
- FCCee-Z $\rho_{e,ave}$=5.5/7+1*6/7=1.64x10^{10} cm^{-3}.

- Threshold

CEPC 4.8e10: $\rho_{e,th}$=2.9x10^{10} m^{-3} , 8e10: $\rho_{e,th}$=2.9x10^{10} m^{-3} ,

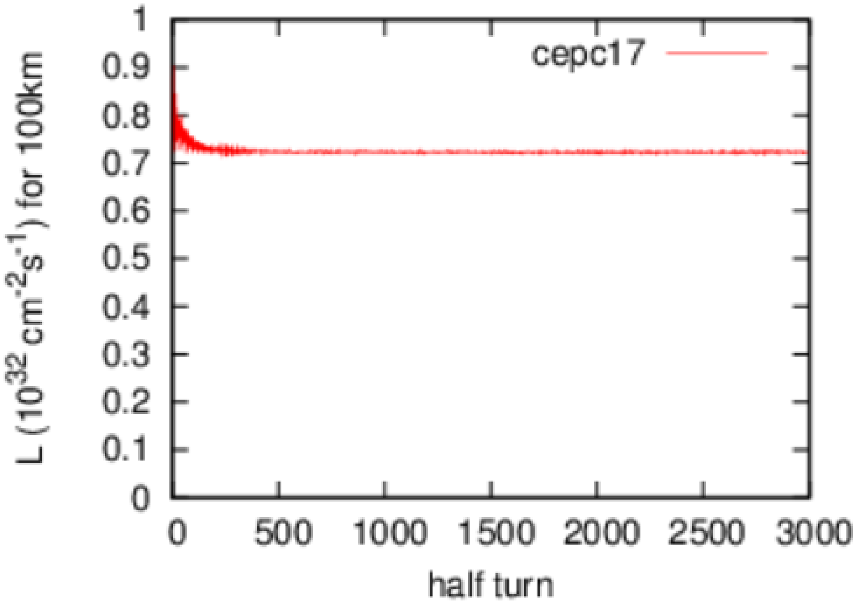
FCCee-Z: $\rho_{e,th}$=1.87x10^{10} m^{-3}

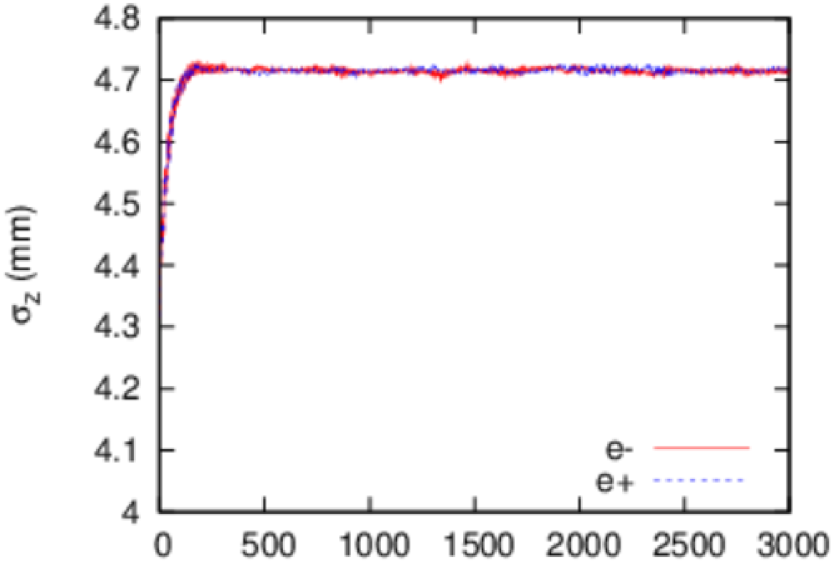
- All 4 cases, Np=4.8e10, Np=8e10, t_{sp}=35ns and 20ns, are stable for electron cloud single bunch instability.

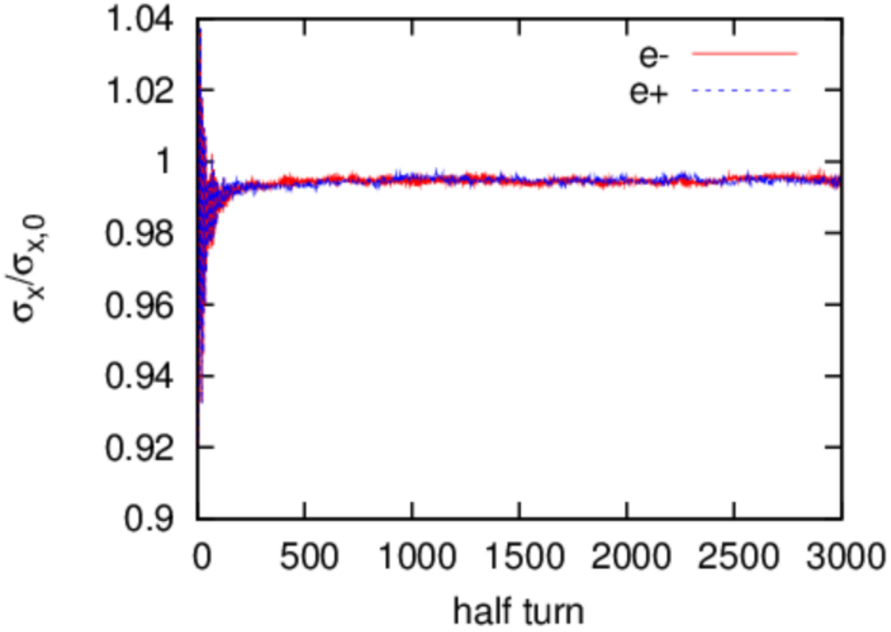
Thank you for your attention

CEPC-H

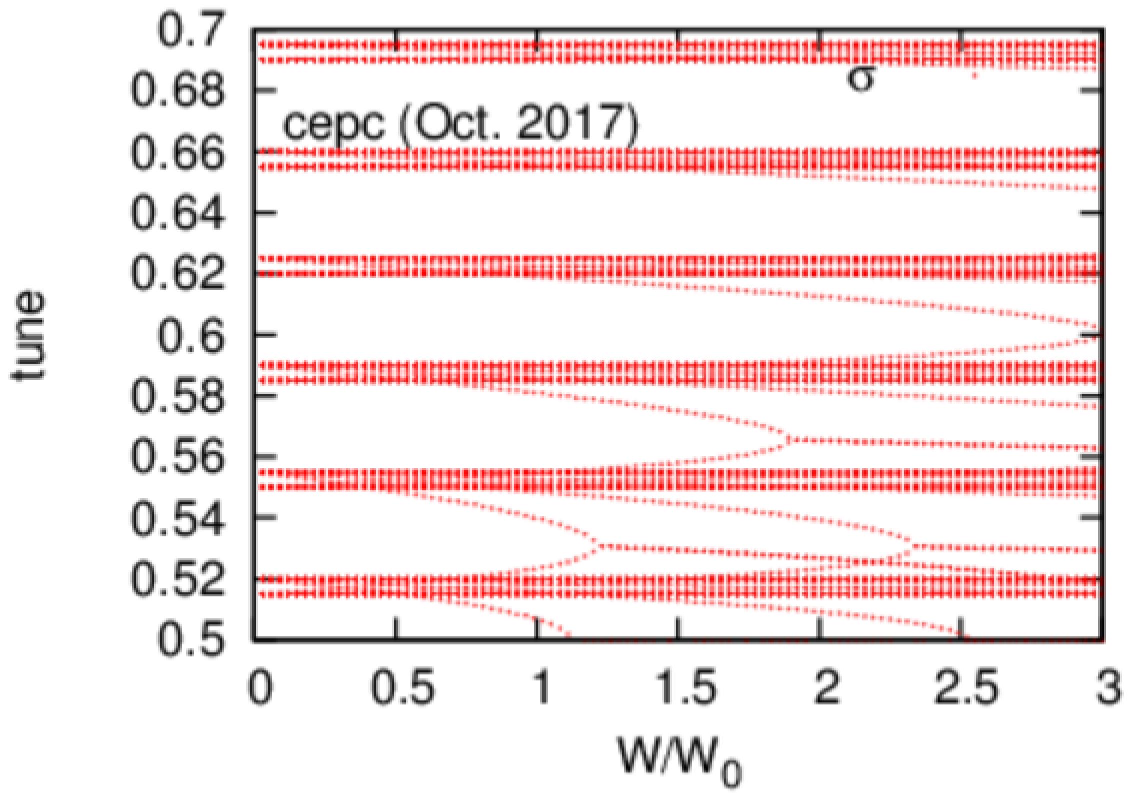
- Y. Zhang, Oct 16, 2017, $\sigma_{z,0}$=3.79mm
- L_{tot}=0.72x10^{32}x286=2.06x10^{34} $cm^{-2}s^{-1}$~ design value.

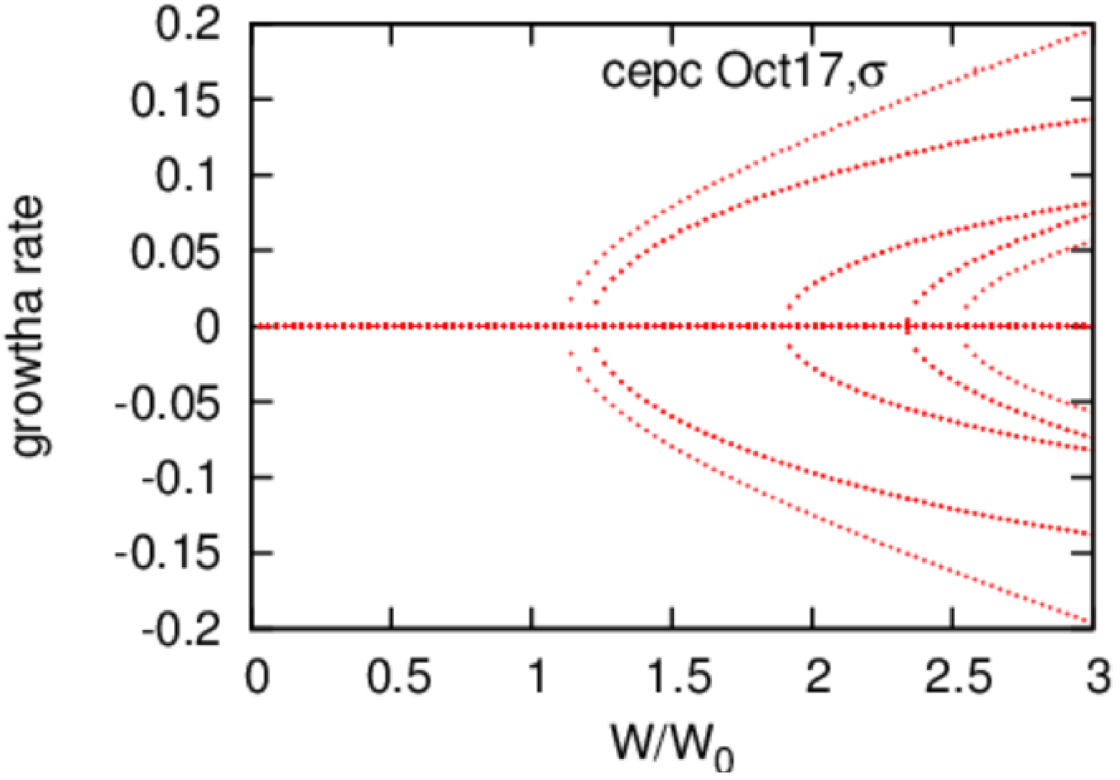






Old


cepc (Oct. 2017)
σ
tune
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0.52
0.5
0
0.5
1
1.5
2
2.5
3
W/W0


cepc Oct17,σ
growtha rate
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.5
1
1.5
2
2.5
3
W/W0